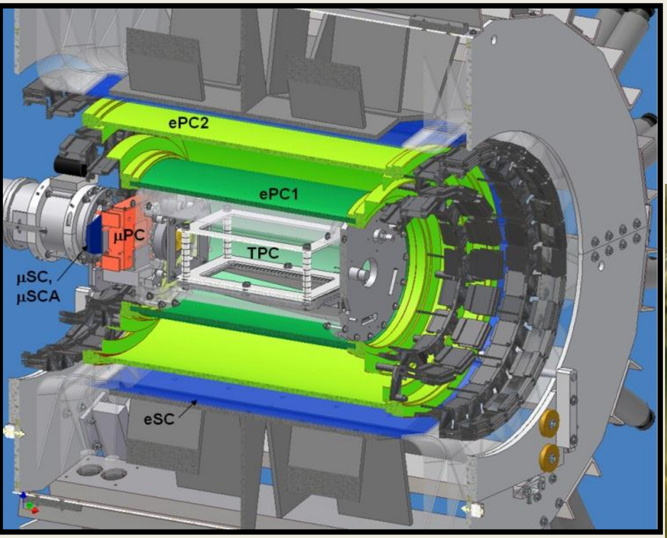
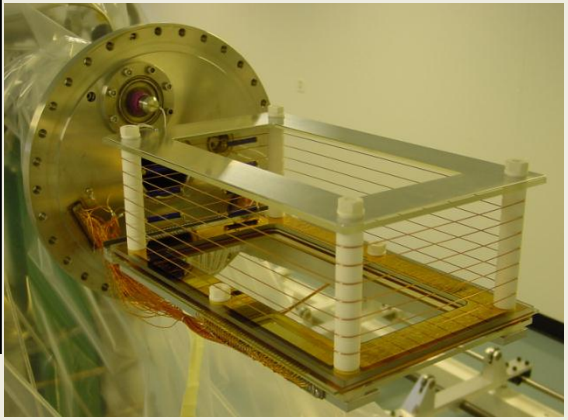
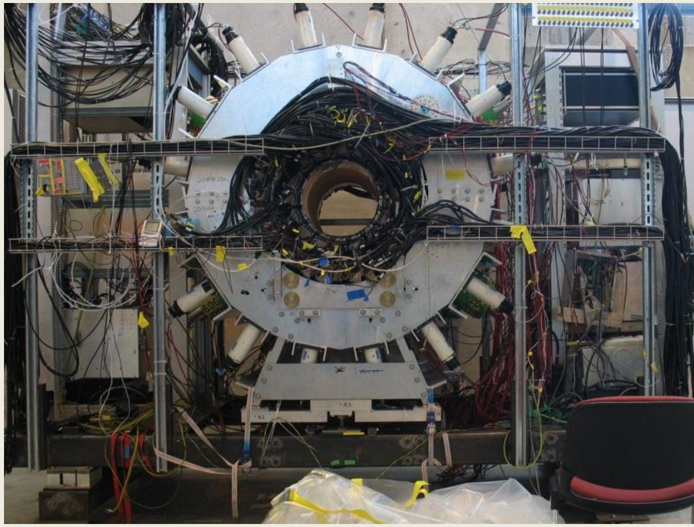
Muon capture on the proton: Final results from the MuCap experiment







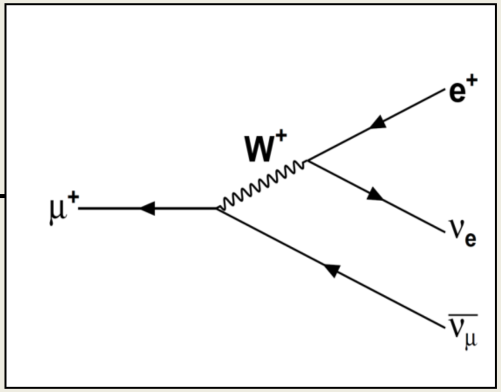
Brendan Kiburg

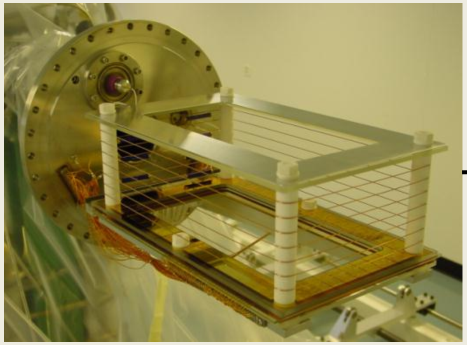
University of Washington

FNAL 4/6/2012

Overview

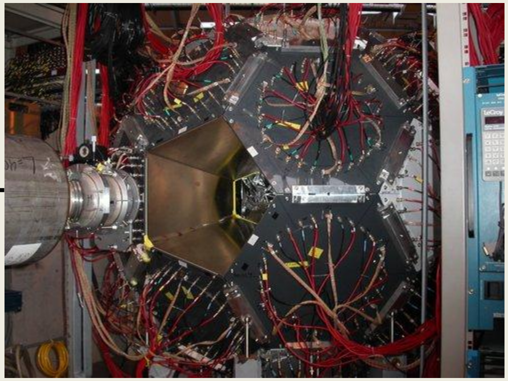
Weak Interaction Physics

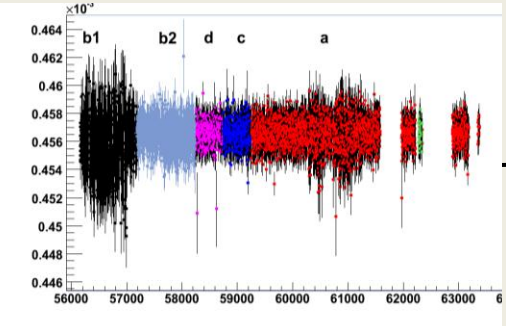




Experimental Requirements

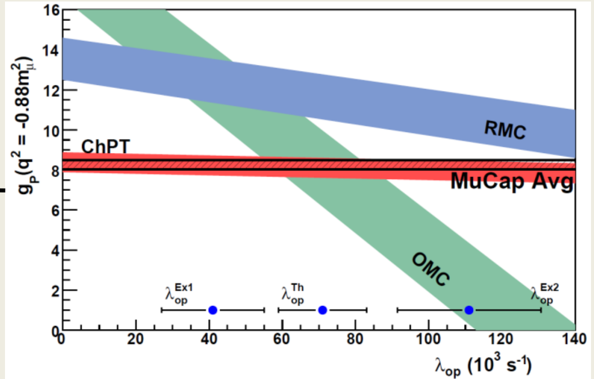
MuLan





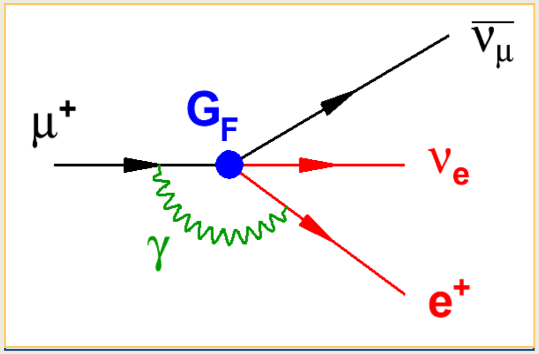
MuCap Analysis

Results



Muons decay via the weak interaction

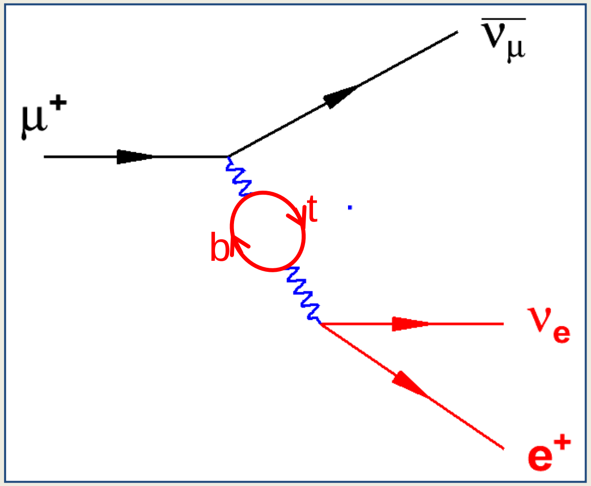
- Fermi contact-interaction



- Rate depends on G_F, strength of weak interaction

$$\lambda_0 = \frac{1}{\tau_\mu} = \frac{G_F^2 m_\mu^5}{192\pi^3}(1 + \delta q)$$

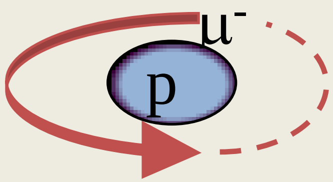
- Modern Feynman diagram



- G_F relates to gauge coupling

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}(1 + \delta r)$$

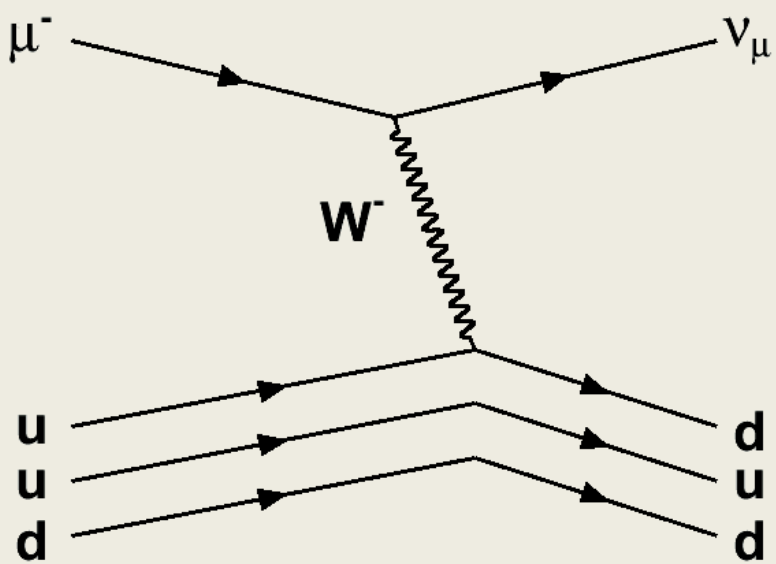
A negative muon can be captured by a proton



$$\boxed{\mu^- + p \to n + \nu_\mu}$$

Rate Λ_S

- Current-current weak interaction



- Leptonic and hadronic left-chiral projections

$$M_{fi} = \frac{G_F V_{ud}}{\sqrt{2}} L_\alpha J^\alpha$$

$$L_\alpha = \bar{u}_\nu \gamma_\alpha \left(1 - \gamma_5\right) u_\mu$$

$$J^\alpha = \bar{q}_d \gamma^\alpha \left(1 - \gamma^5\right) q_u$$

The quarks involved in muon capture are embedded in a nucleon; the hadronic current must be modified

$$J^\alpha = \bar{u}_n \left(\underbrace{g_V \gamma^\alpha + \frac{i g_M}{2m_N}\sigma^{\alpha\nu} q_\nu + \cancel{\frac{g_S}{m_\mu}} q^\alpha}_{V^\alpha} - \underbrace{g_A \gamma^\alpha \gamma_5 - \frac{g_P}{m_\mu} q^\alpha \gamma_5 - \cancel{\frac{i g_T}{2m_N}} \sigma^{\alpha\nu} q_\nu \gamma_5}_{A^\alpha} \right) u_p$$

- CVC + G-Parity
  - g_S , $g_T \approx 0$
- CVC + Electron scattering
  - $g_V(q_\mu^2) = 0.976 \pm 0.001$
  - $g_M(q_\mu^2) = 3.583 \pm 0.003$
- Neutron beta decay
  - $g_A(q_\mu^2) = 1.247 \pm 0.004$
- This leaves g_P
  - Known with ≈50% uncertainty

Spontaneous Symmetry Breaking connects g_P to the pion

- Vector (CVC)
- $\partial_\alpha V^\alpha = 0$

- Axial (PCAC)
- $\partial_\alpha A^\alpha = 0$ (chiral limit)

AXIAL VECTOR CURRENT CONSERVATION IN WEAK INTERACTIONS*

Yoichiro Nambu
Enrico Fermi Institute for Nuclear Studies and Department of Physics
University of Chicago, Chicago, Illinois
(Received February 23, 1960)

$\Downarrow$

2008 Nobel Prize

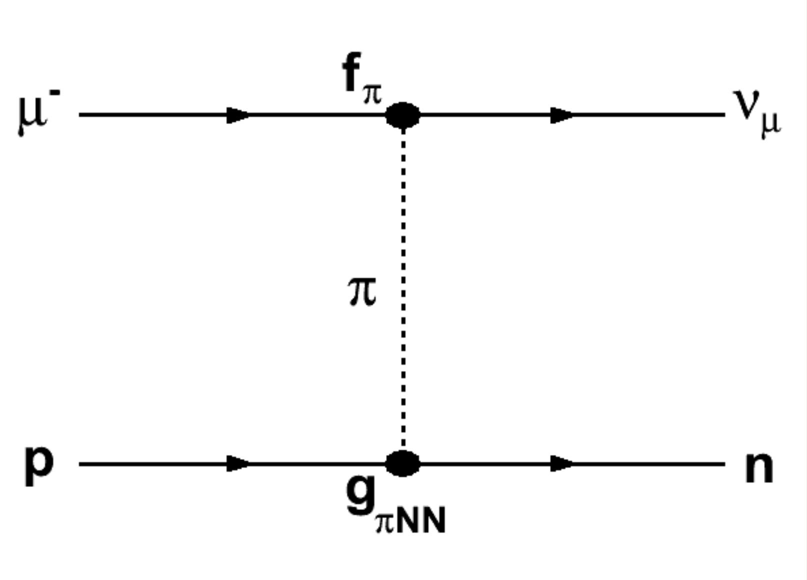
- Nambu realized:
  - If A^α conserved:
    - Chiral symmetry is spontaneously broken
    - A massless pseudoscalar exists
  - Explicit chiral breaking
    - $\partial_\alpha A^\alpha(x) \propto \varphi(x)$ (pion field)
    - The (massive) pion is the pseudo-Nambu-Goldstone boson
- Historic milestone:
  - Foundation for the generation of particle masses
  - Led to development of chiral perturbation theory, low-energy effective field theory of fundamental QCD

Modern theory makes precise predictions for g_P

- Chiral Perturbation Theory (ChPT)
  - Effective field theory
  - Systematic low-energy expansion valid for q small compared to chiral scale

$$g_P(q^2) = \frac{2m_\mu g_{\pi NN} f_\pi}{m_\pi^2 - q^2} - \frac{1}{3} g_A(0) m_\mu m_N r_A^2$$

$$(8.74 \pm 0.23) - (0.48 \pm 0.02)$$

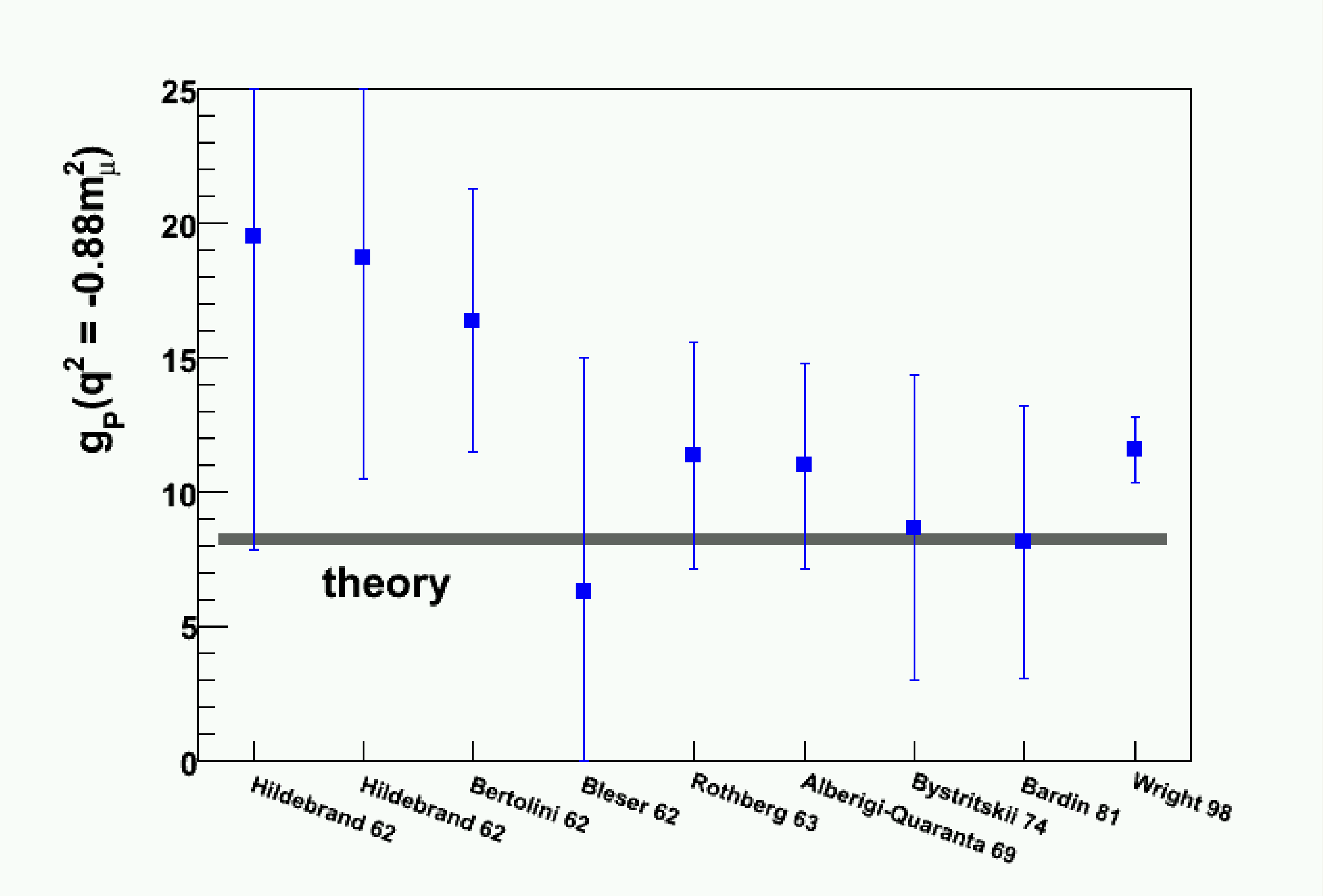


$g_P = (8.74 \pm 0.23) - (0.48 \pm 0.02) = 8.26 \pm 0.23$

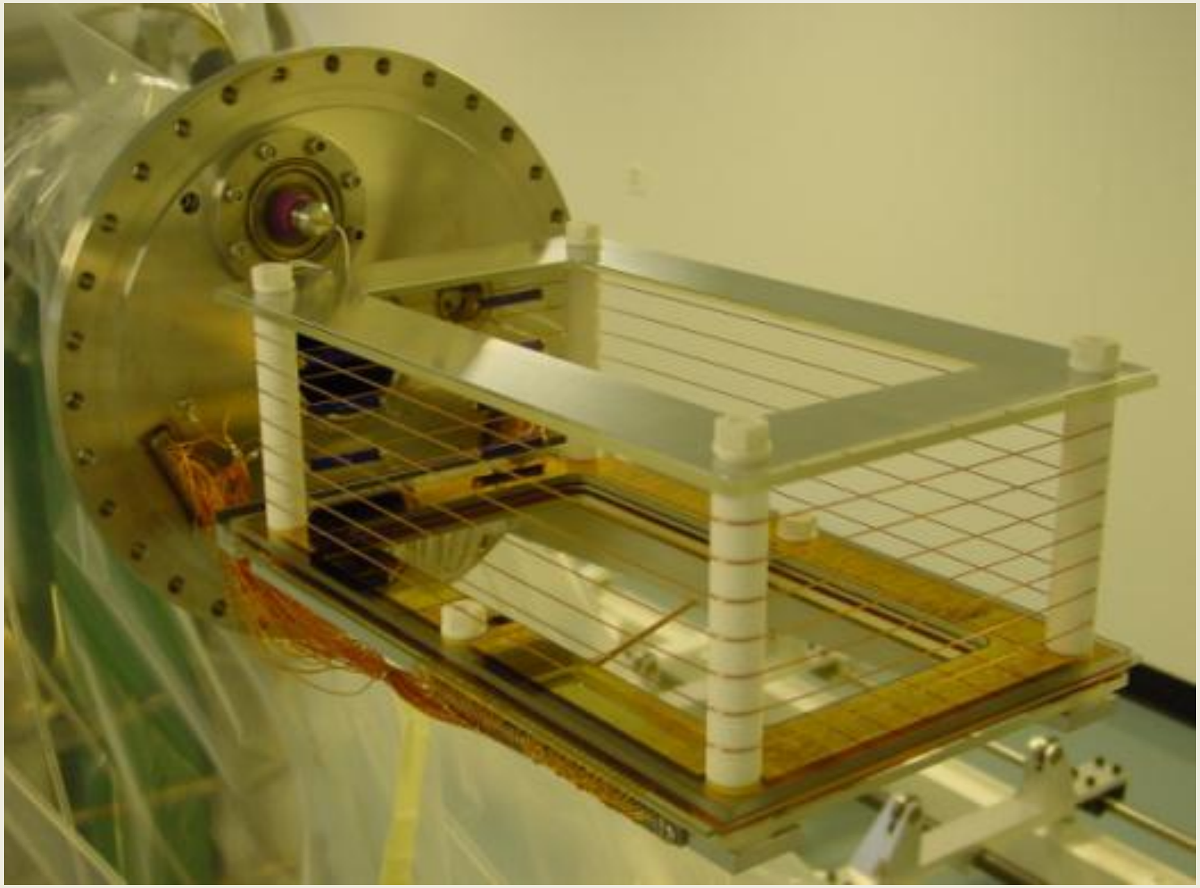
$$M_{fi} = \frac{G_F V_{ud}}{\sqrt{2}} L_\alpha J^\alpha$$

$\Lambda_S^{Theory} = 711.5 \pm 4.6\ s^{-1} (0.65\%)$

The experimental determinations of g_P prior to MuCap were far less precise

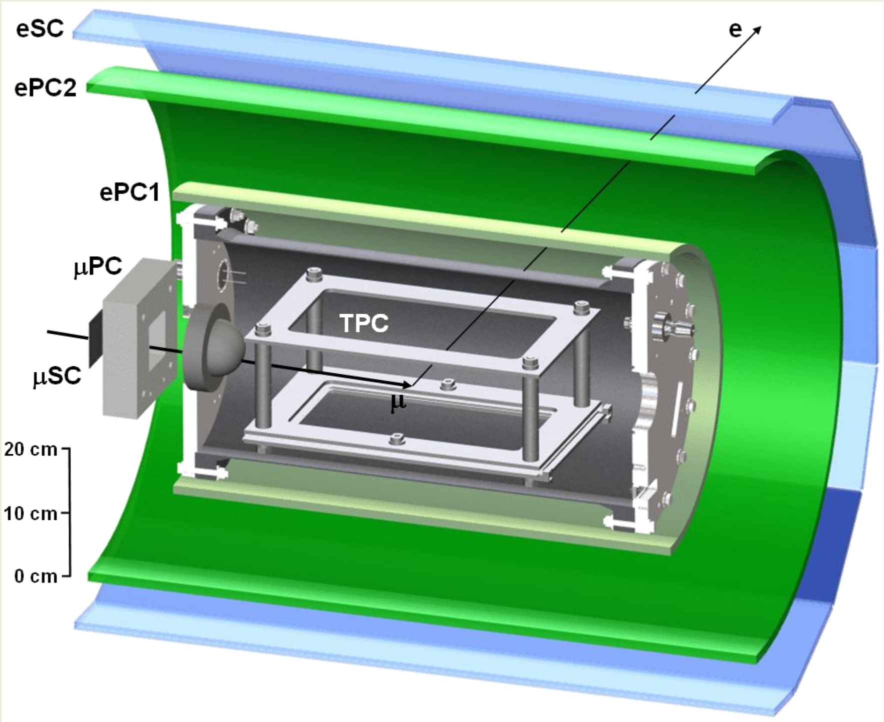


Experimental Requirements



MuCap experimental requirements

- Use a low-energy muon beam
- Stop in a specially prepared pure hydrogen target
- Image the stopping muon (TPC)
- Measure the disappearance rate
- Compare to the positive muon lifetime (MuLan)



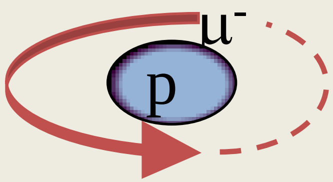
How can one measure the capture rate, Λ_S ?

$$\boxed{\mu^- + p \rightarrow n + \nu_\mu}$$

Could try a direct measurement

- Limited by knowledge of absolute detection efficiency
- Past efforts produced ~10% precision

MuCap uses the lifetime method to determine the capture rate, Λ_S

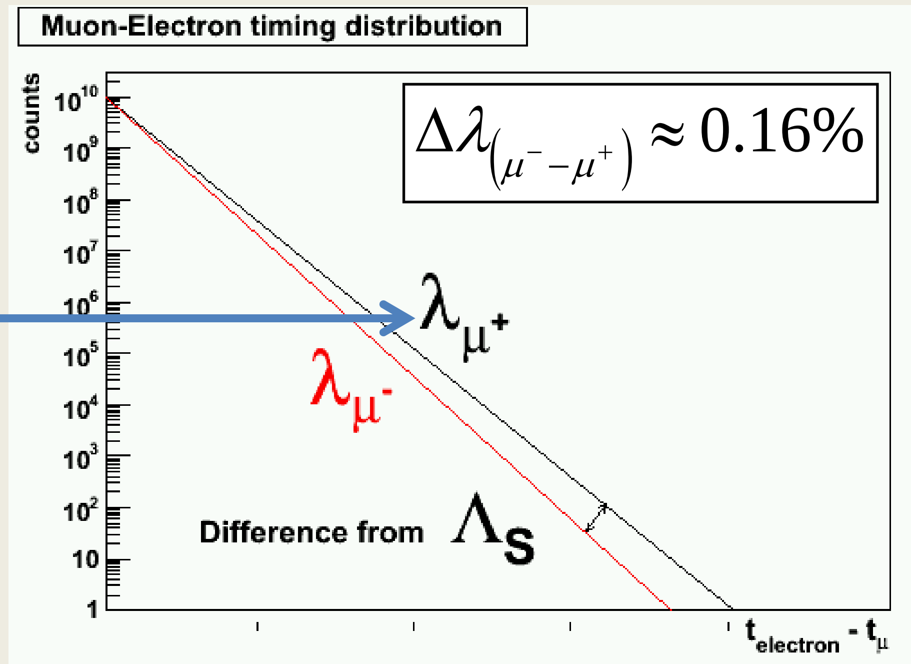


$$\boxed{\mu^- + p \rightarrow n + \nu_\mu}$$ (~700 s^{-1})

$$\boxed{\mu^- + p \rightarrow p + e^- + \bar{\nu}_e + \nu_\mu}$$ (~455000 s^{-1})

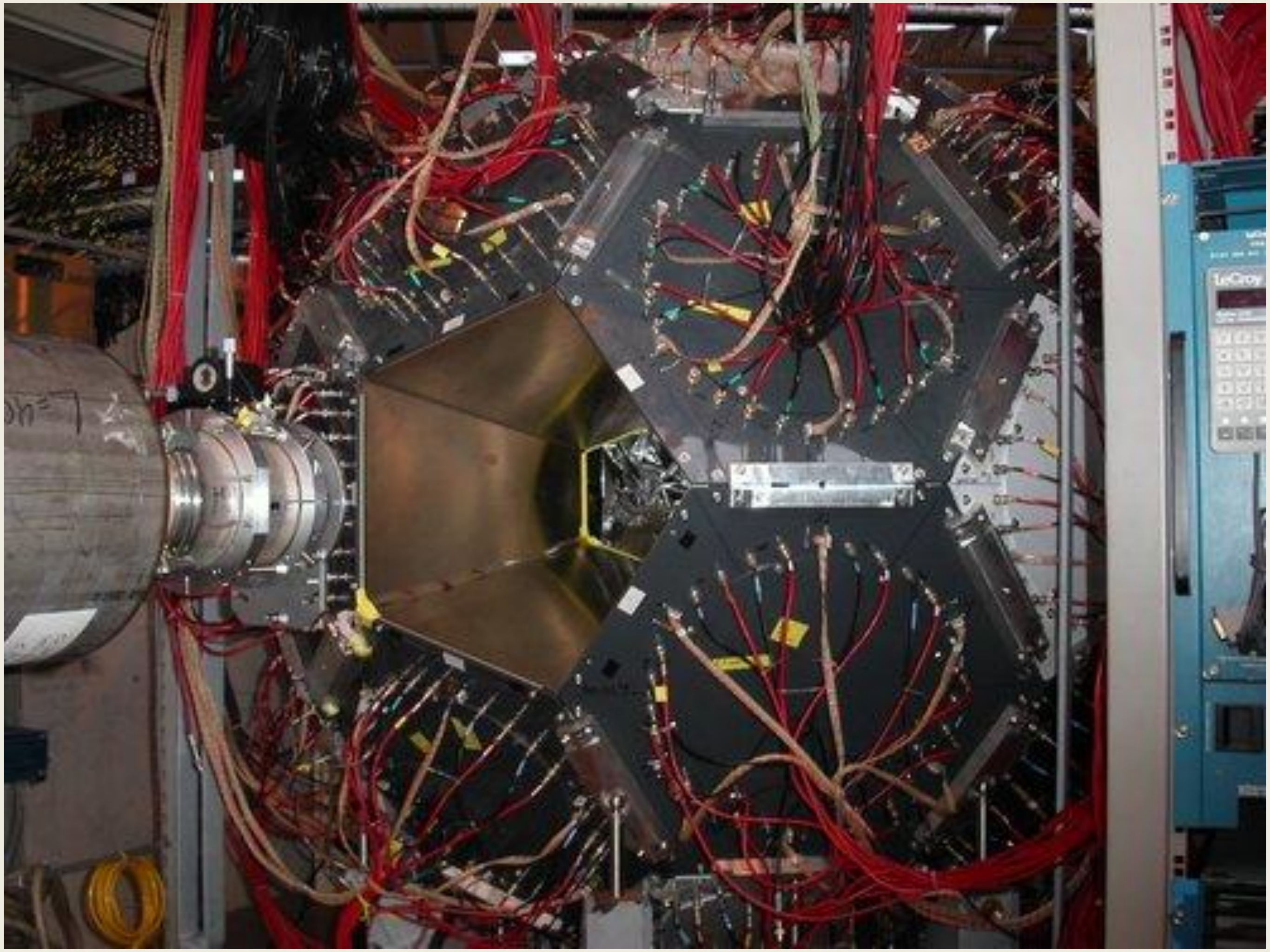
We observe the electron from muon decay.

MuLan!



$$\Lambda_S \approx \lambda_{\mu^-} - \lambda_{\mu^+}$$

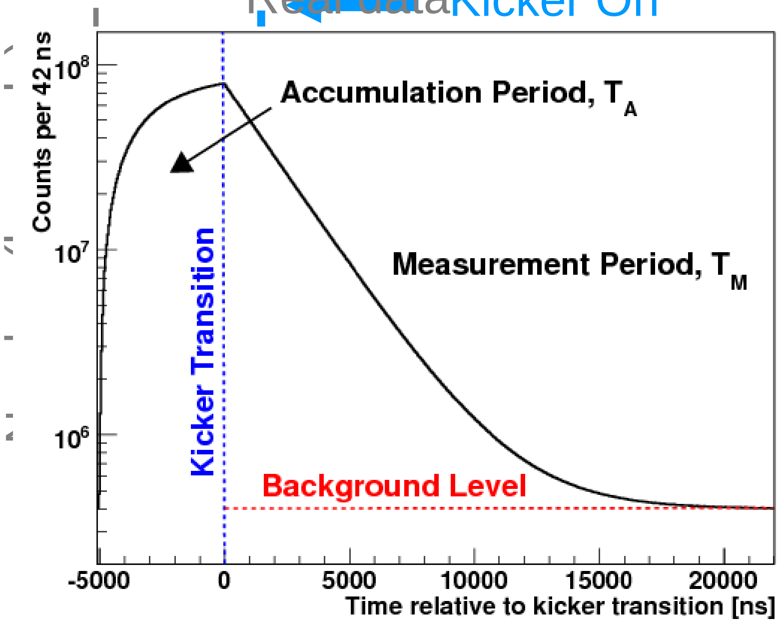
The MuLan Experiment



MuLan!

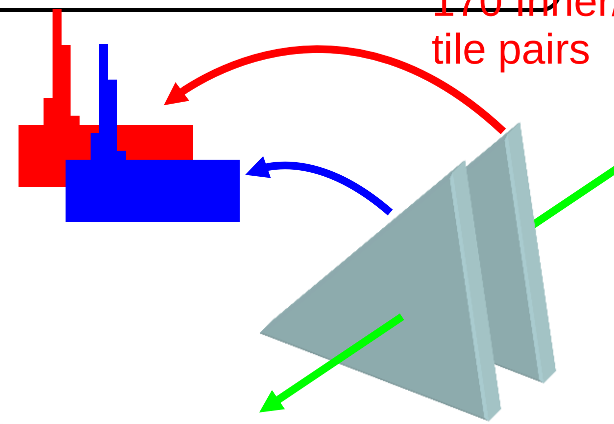
The experimental concept…

Real data Kicker On

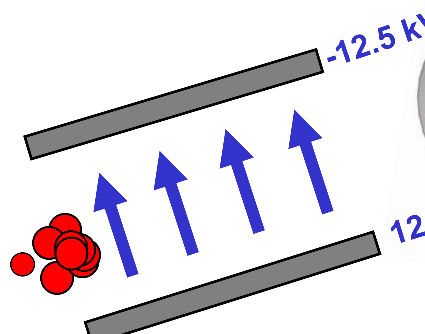


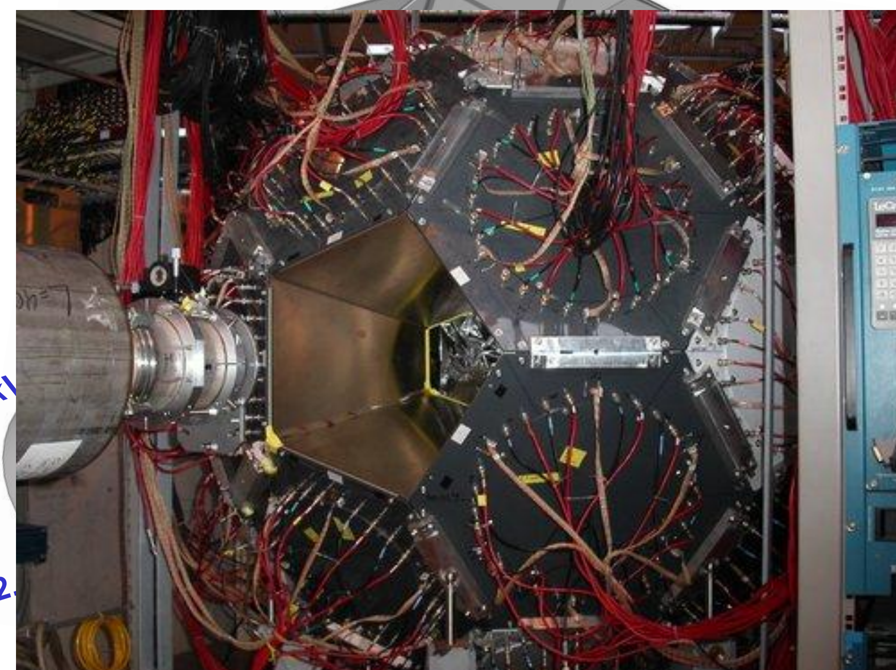
450 MHz WaveForm Digitization (2006/07)

170 Inner/Outer tile pairs



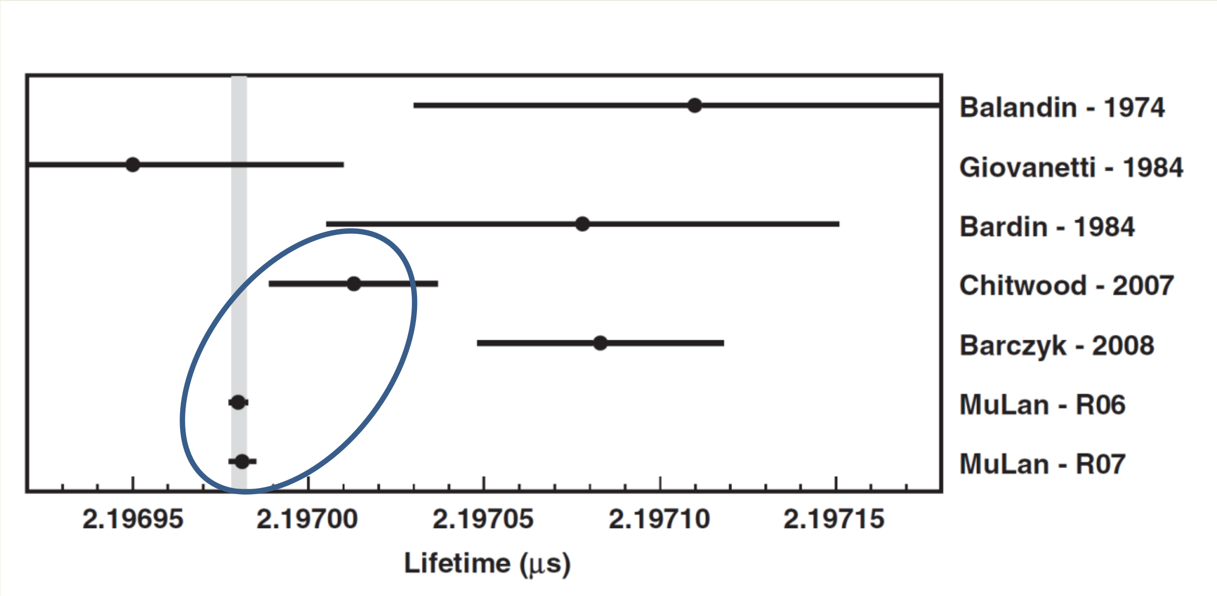
od





MuLan!

In 2011, MuLan published a new result for the positive muon lifetime

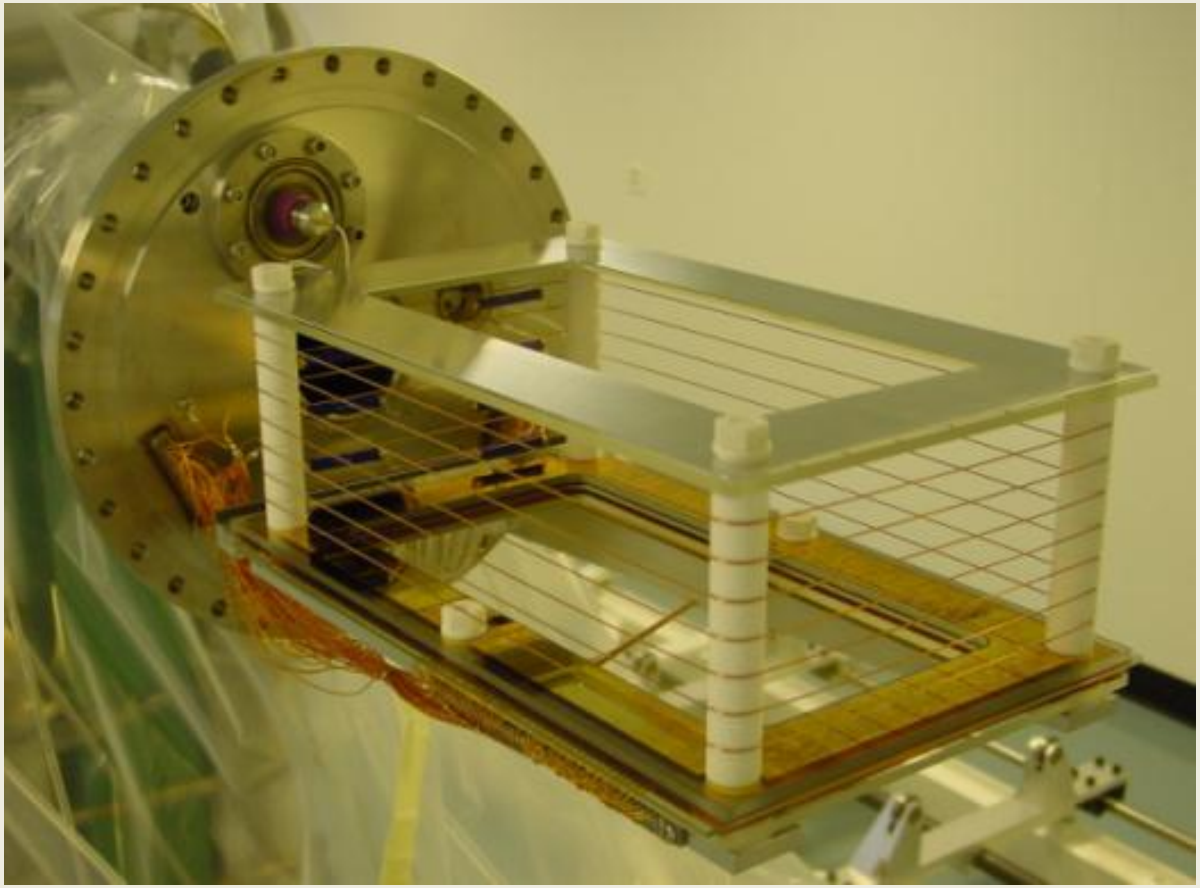


- New MuLan result

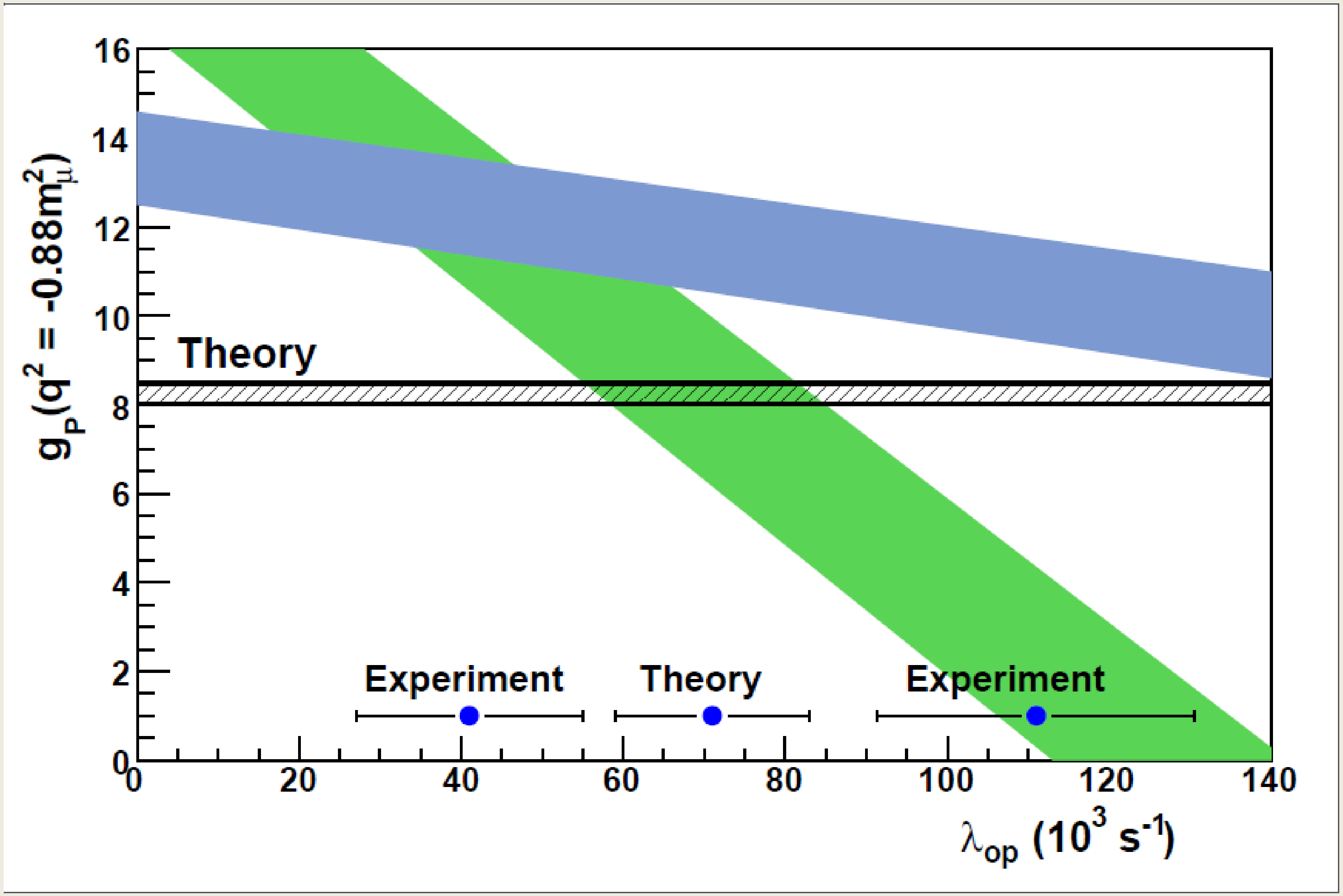
(Webber et al. PRL 106, 2011)

- $\tau_{\mu^+} = 2196980.3 \pm 2.2 \text{ ps}$ (1 ppm)
- $G_F = 1.1663788(7) \times 10^{-5} \text{ GeV}^{-2}$ (0.6 ppm)
- $\lambda_{\mu^+} = 455170.2 \pm 0.46 \text{ s}^{-1}$

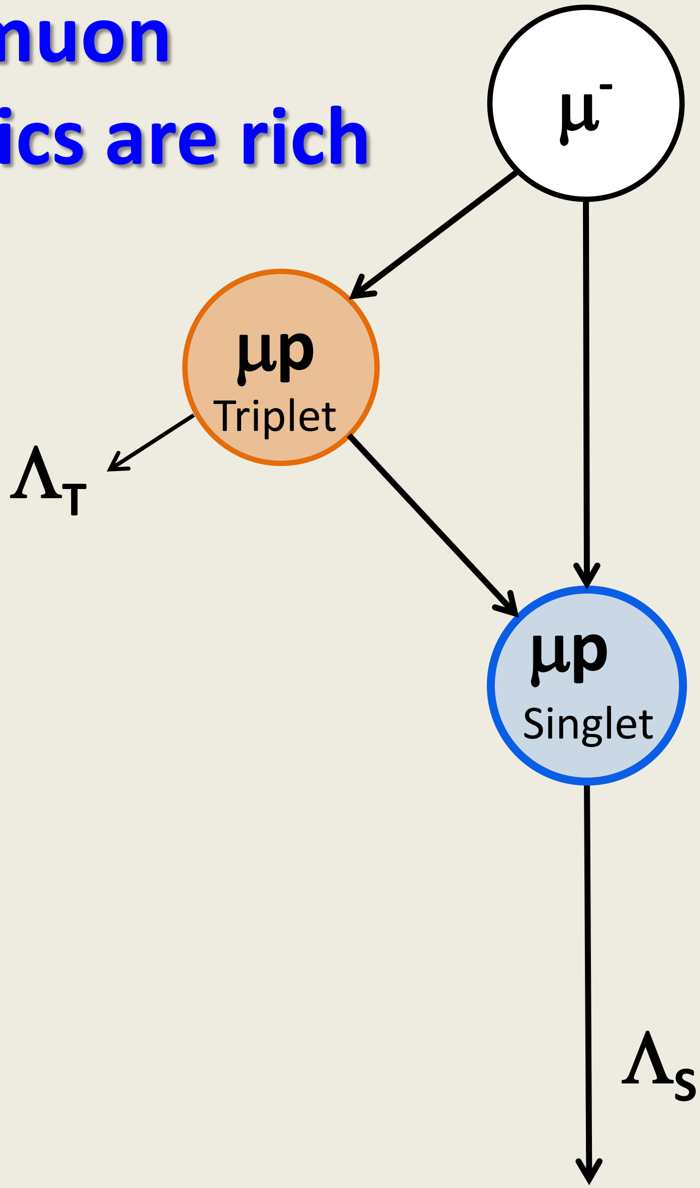
Hydrogen Target Requirements



Past experiments were very sensitive to a poorly known parameter of muon chemistry

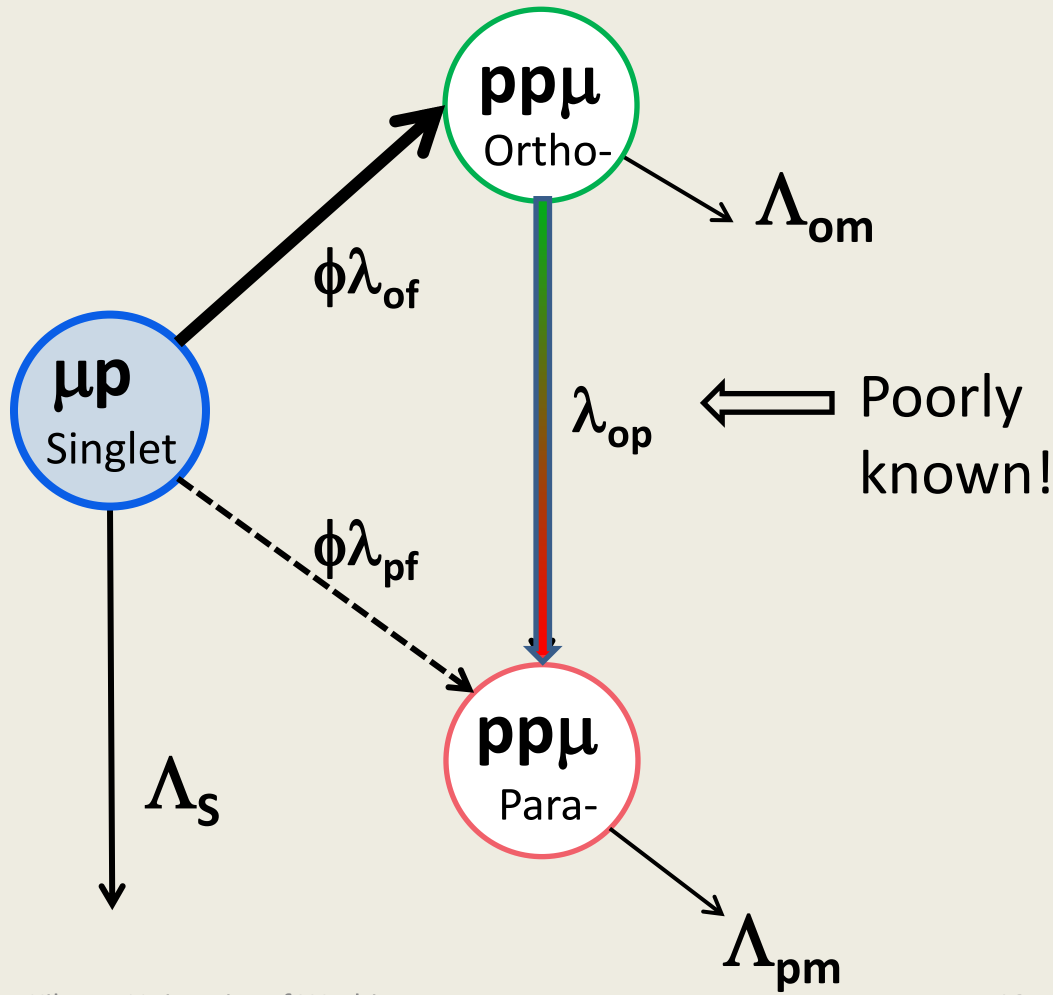


The muon kinetics are rich



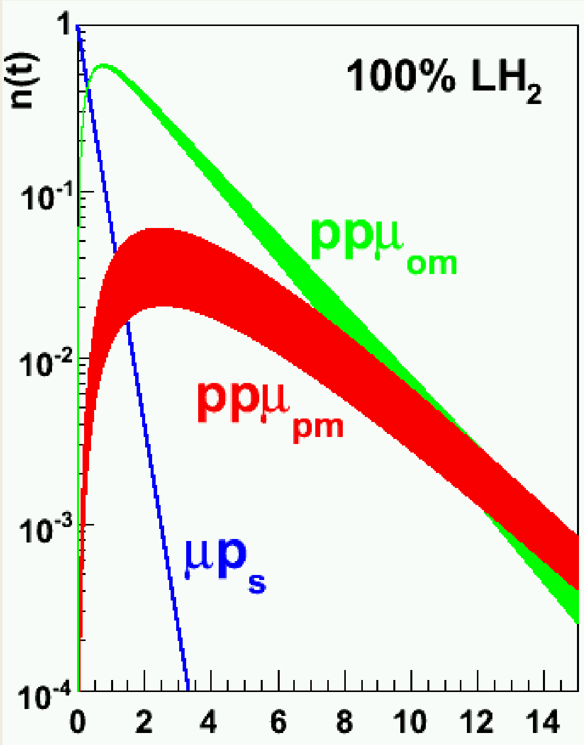
- Decay from any state
- Atomic capture
- Populate singlet state ≈10 ns

- $\Lambda_S \sim 700\ s^{-1}$
- $\Lambda_T \sim 12\ s^{-1}$
- Strong spin dependence

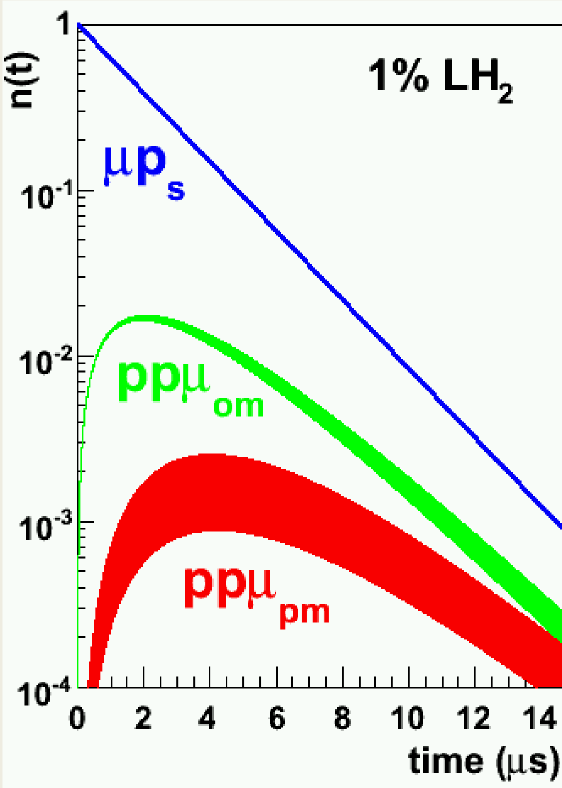

ppμ
Ortho-
Λom
φλof
μp
Singlet
λop
Poorly
known!
φλpf
ppμ
Para-
ΛS
Λpm

Molecular formation distorts the disappearance rate of the μp system, in a time-dependent way

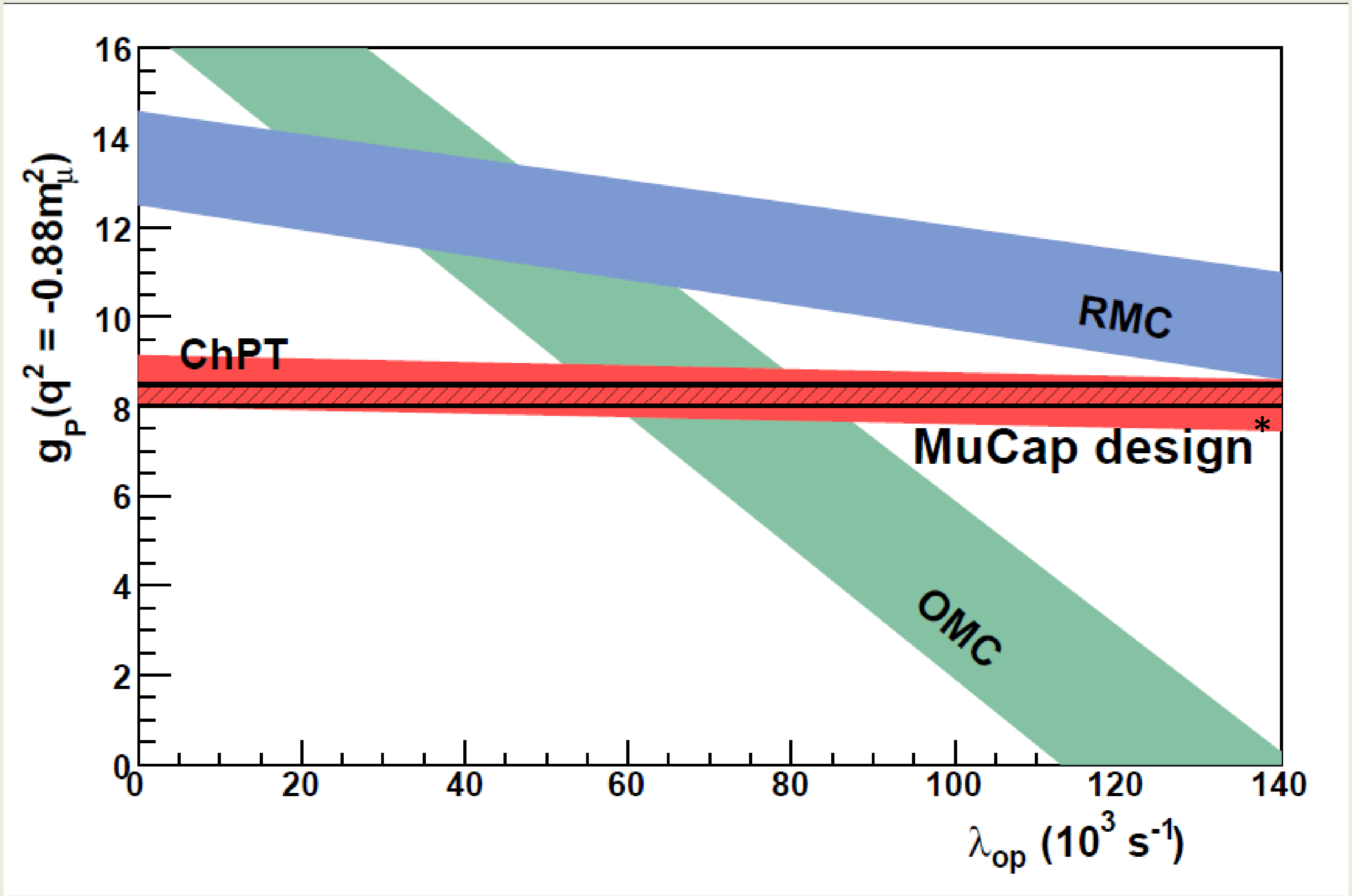
- Capture rate depends on spin configuration
- Relative population is a function of kinetic rates (λ_{of} ,λ_{op})
- Molecular formation rate is a function of hydrogen density, ϕ



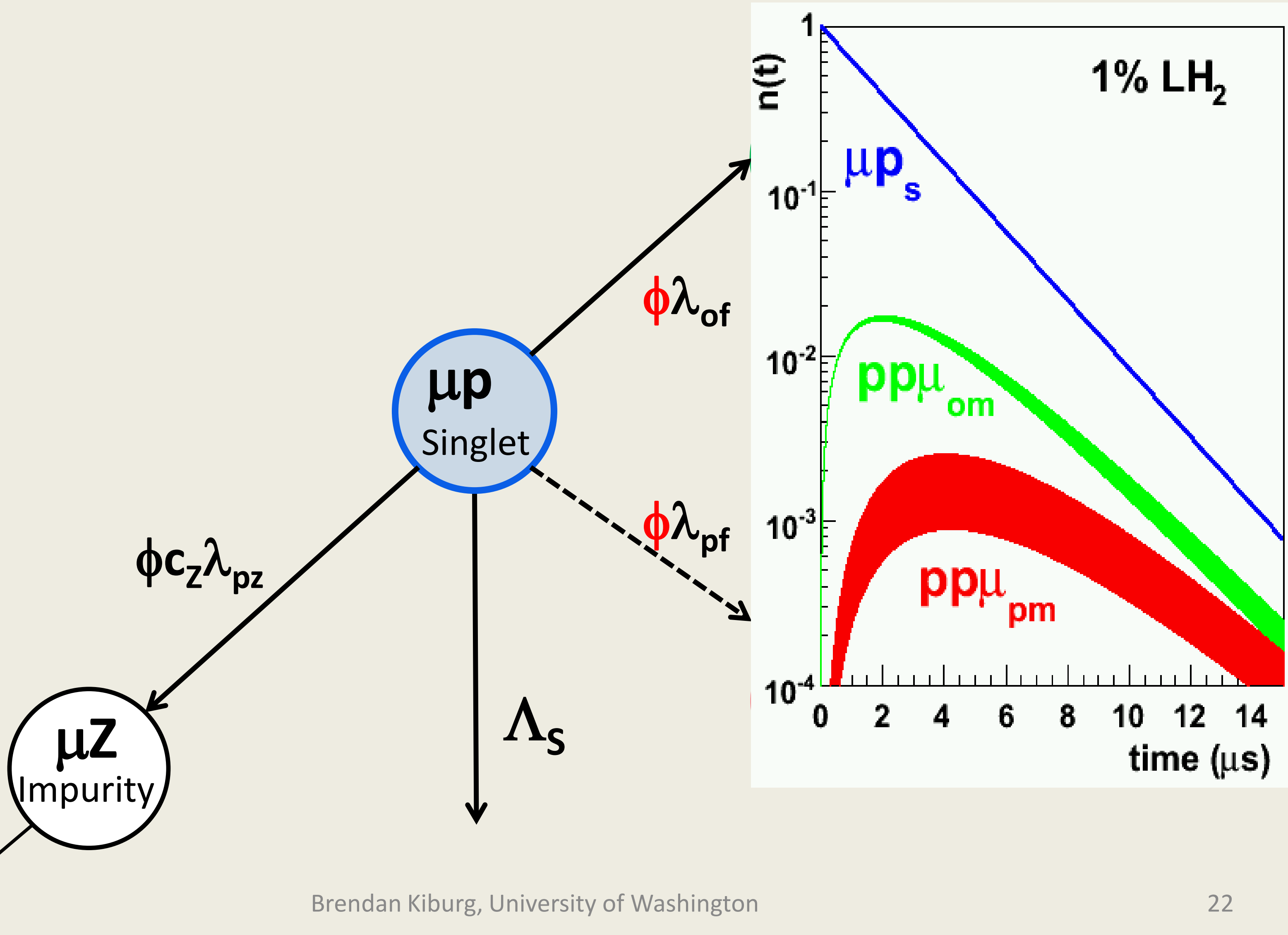
- $\Lambda_S \sim 700\ s^{-1}$
- ~~$\Lambda_{OM} \sim 3/4\ \Lambda_S$~~ (540 s^{-1})
- ~~$\Lambda_{PM} \sim 1/4\ \Lambda_S$~~ (210 s^{-1})



MuCap is designed to be mostly insensitive to the molecular complexities



*MuCap design is drawn centered on the theory value



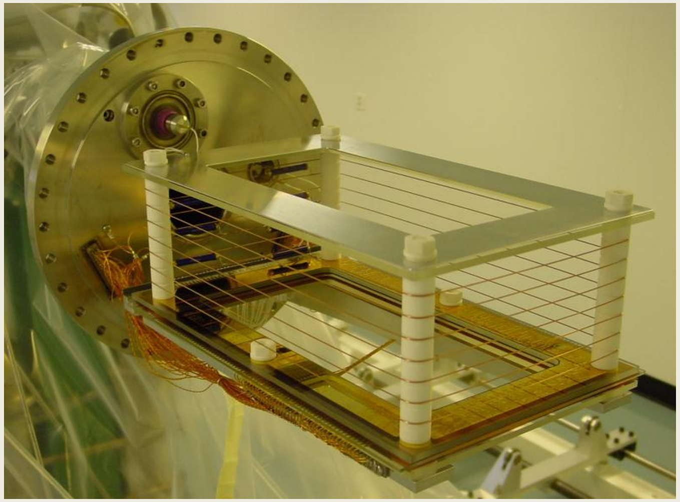
μp
Singlet
φλof
φλpf
φcZλpz
μZ
Impurity
ΛS
ΛZ
n(t)
1% LH2
μps
ppμom
ppμpm
1
10-1
10-2
10-3
10-4
0 2 4 6 8 10 12 14
time (μs)

High-Z impurities have a larger capture rate and should be removed from the target

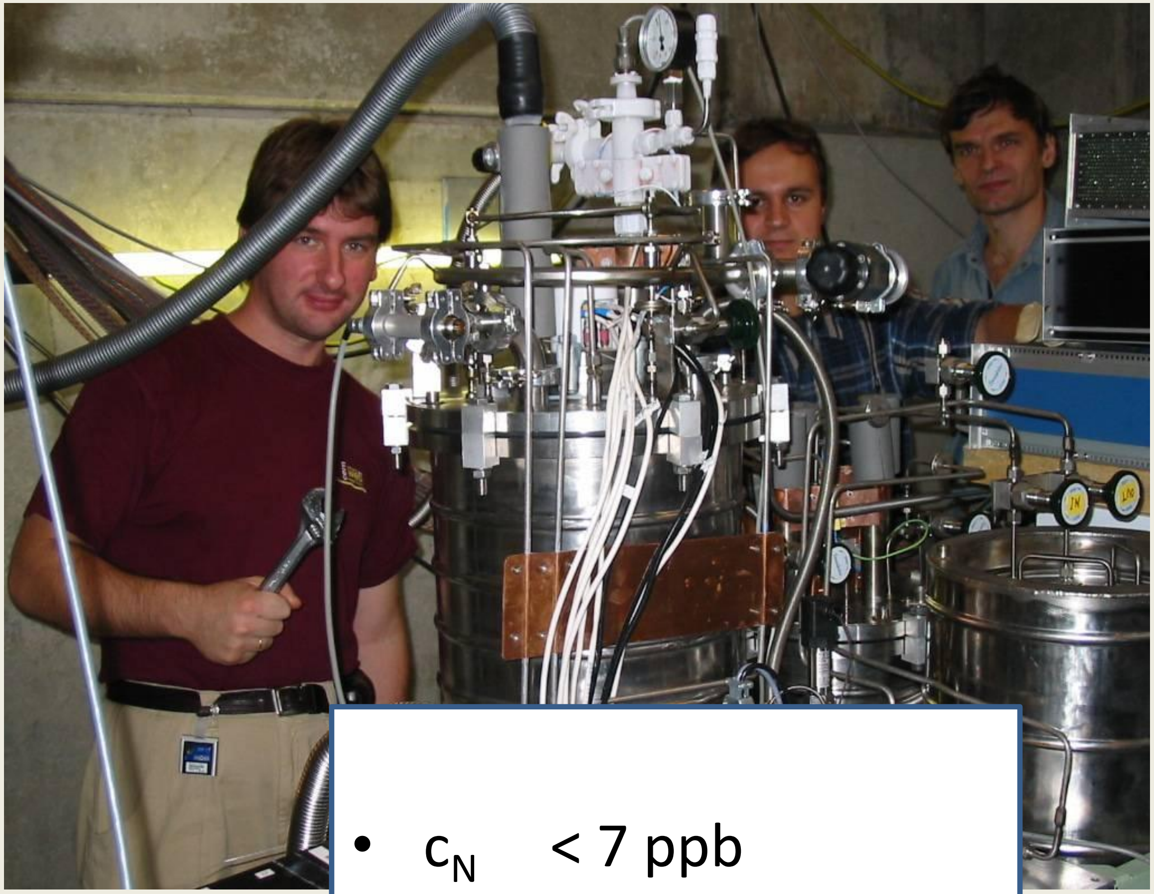
"High-Z" = Z > 1

$$\Lambda_Z \propto Z^4$$

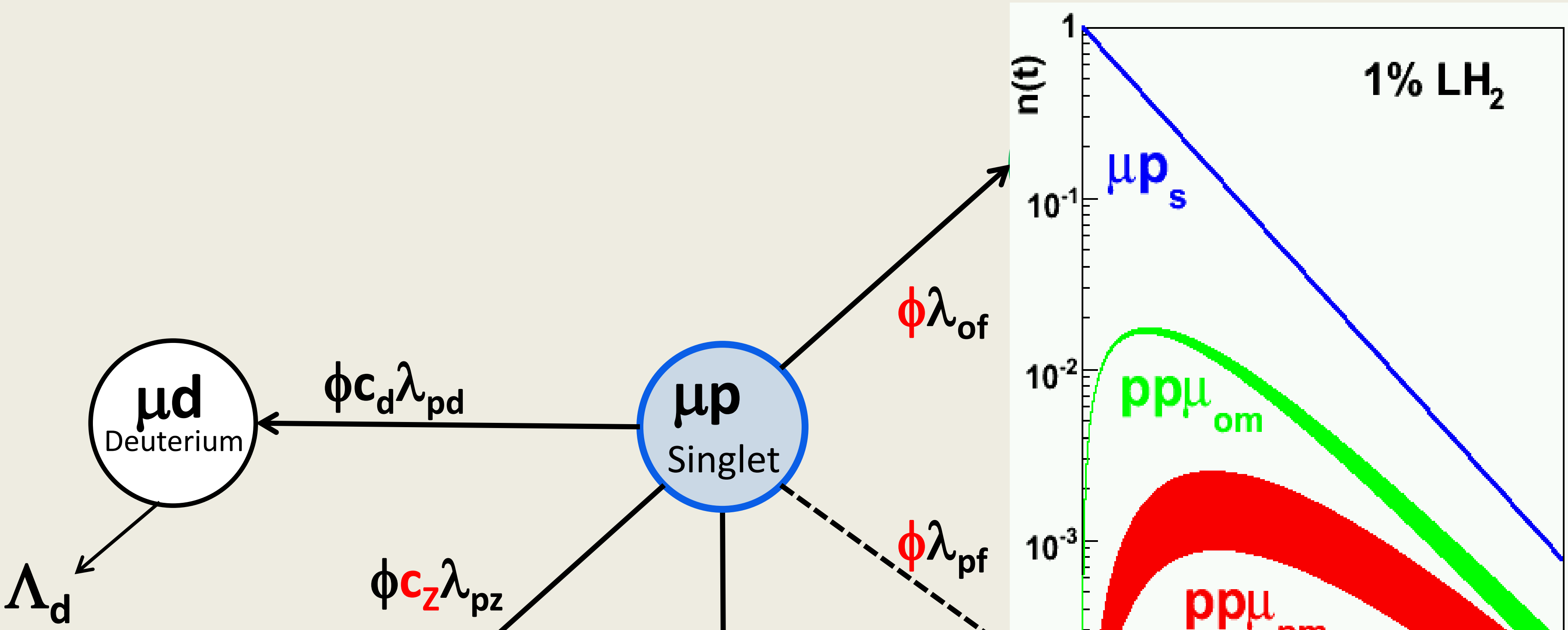
- Active TPC
- No materials in fiducial volume

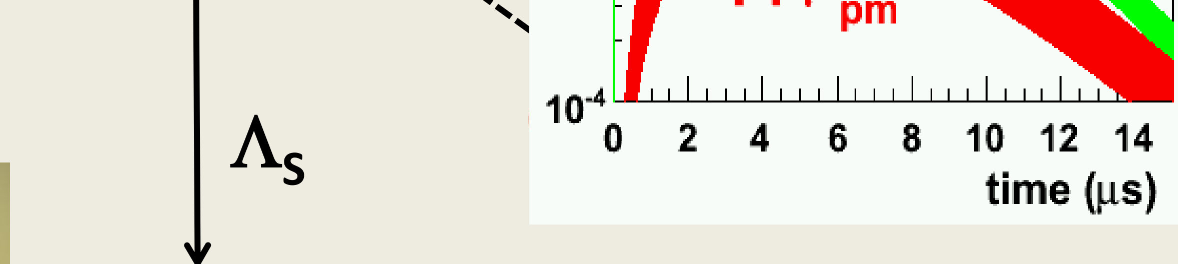


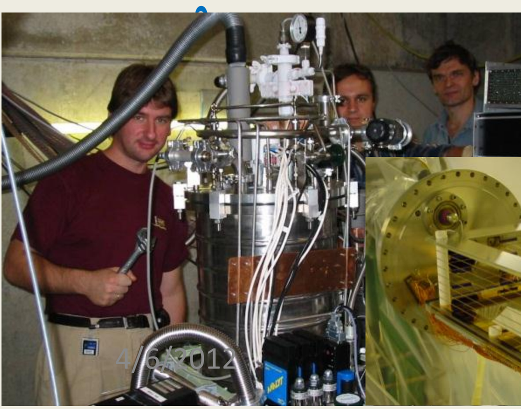
- CHUPS purifies the gas continuously

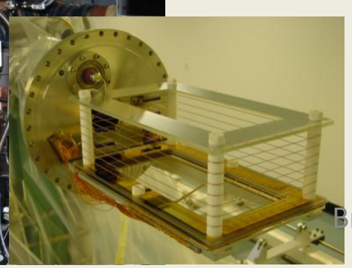


- c_N < 7 ppb
- c_{H_2O} < 10 ppb


μd
Deuterium
μp
Singlet
$\phi c_d \lambda_{pd}$
Λ_d
$\phi c_Z \lambda_{pz}$
Λ_S
$\phi\lambda_{of}$
$\phi\lambda_{pf}$
n(t)
1% LH_2
μp_s
$pp\mu_{om}$
$pp\mu_{pm}$
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0 2 4 6 8 10 12 14
time (μs)

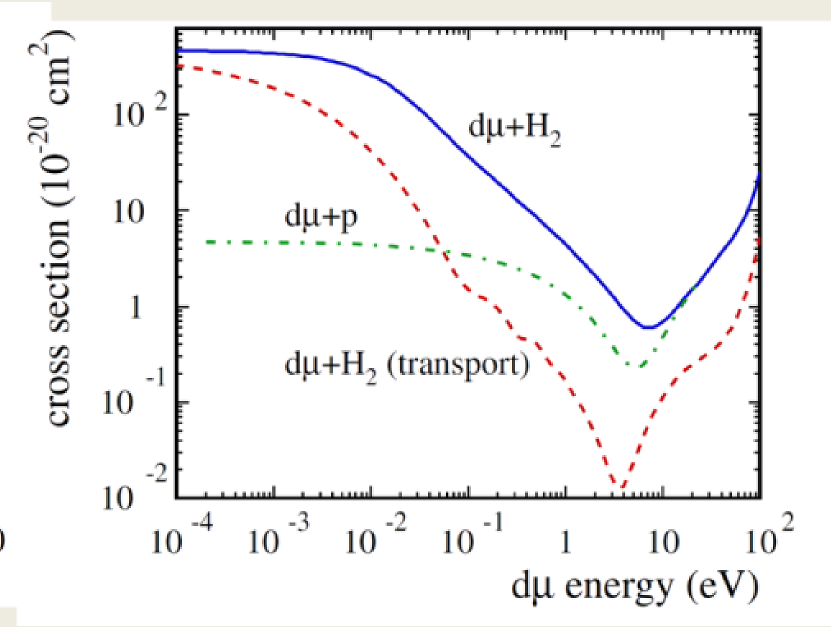


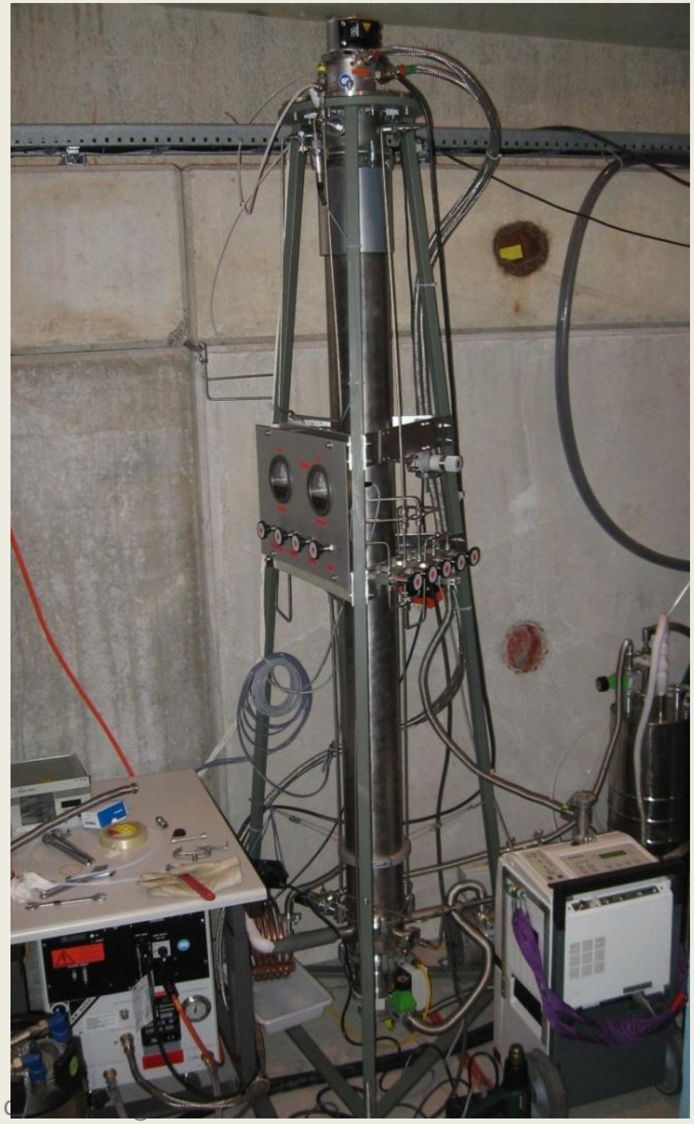




μd diffusion

μ forms μd atom
Ramsauer-Townsend minimum

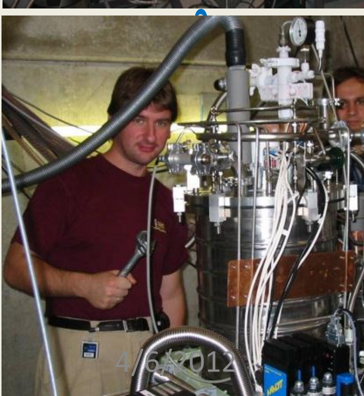


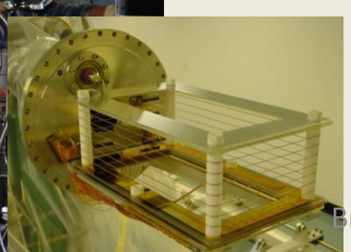


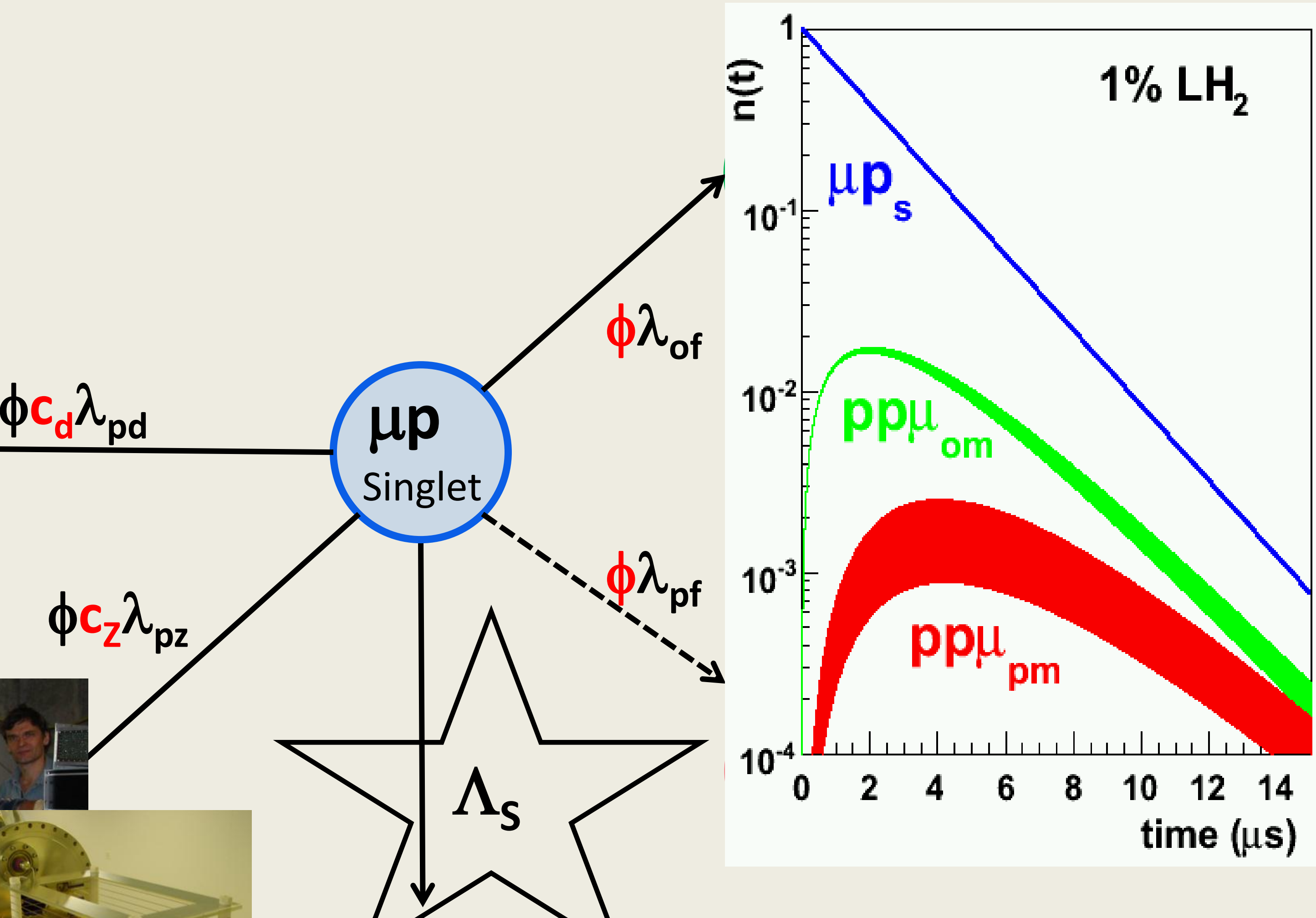
Cryogenic distillation column
Isotopic separation

$c_d < 6$ ppb

The careful choice of operating conditions makes this experiment possible

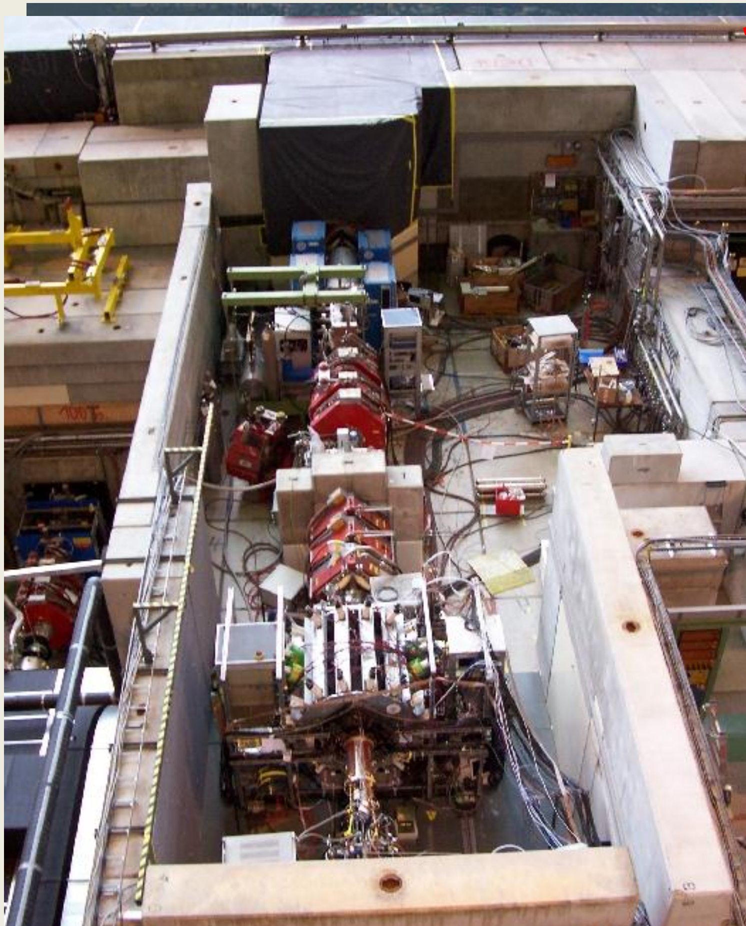


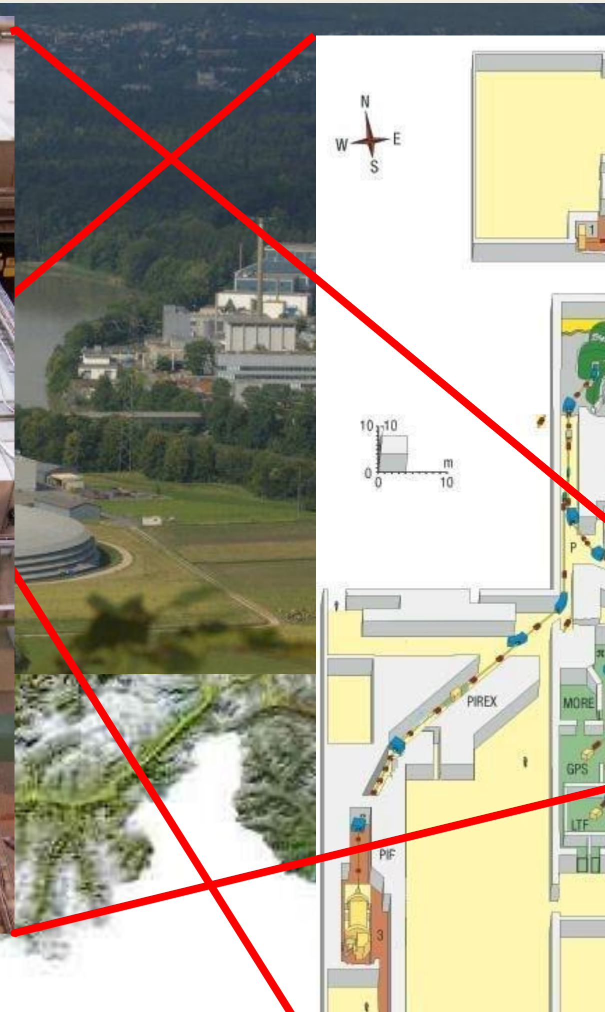


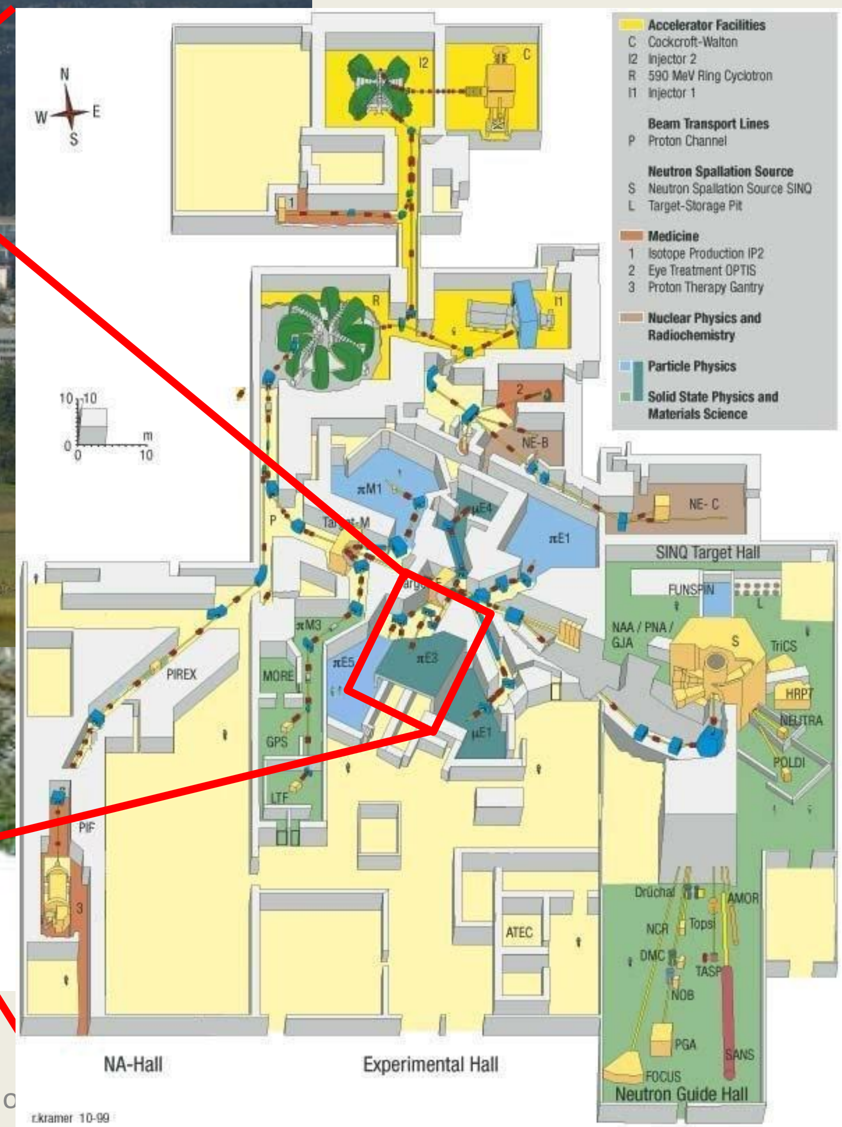


For 10 ppm, we need more than 10^{10} muons ...

- 1.3 MW beam; 2.2 mA, 590 MeV protons

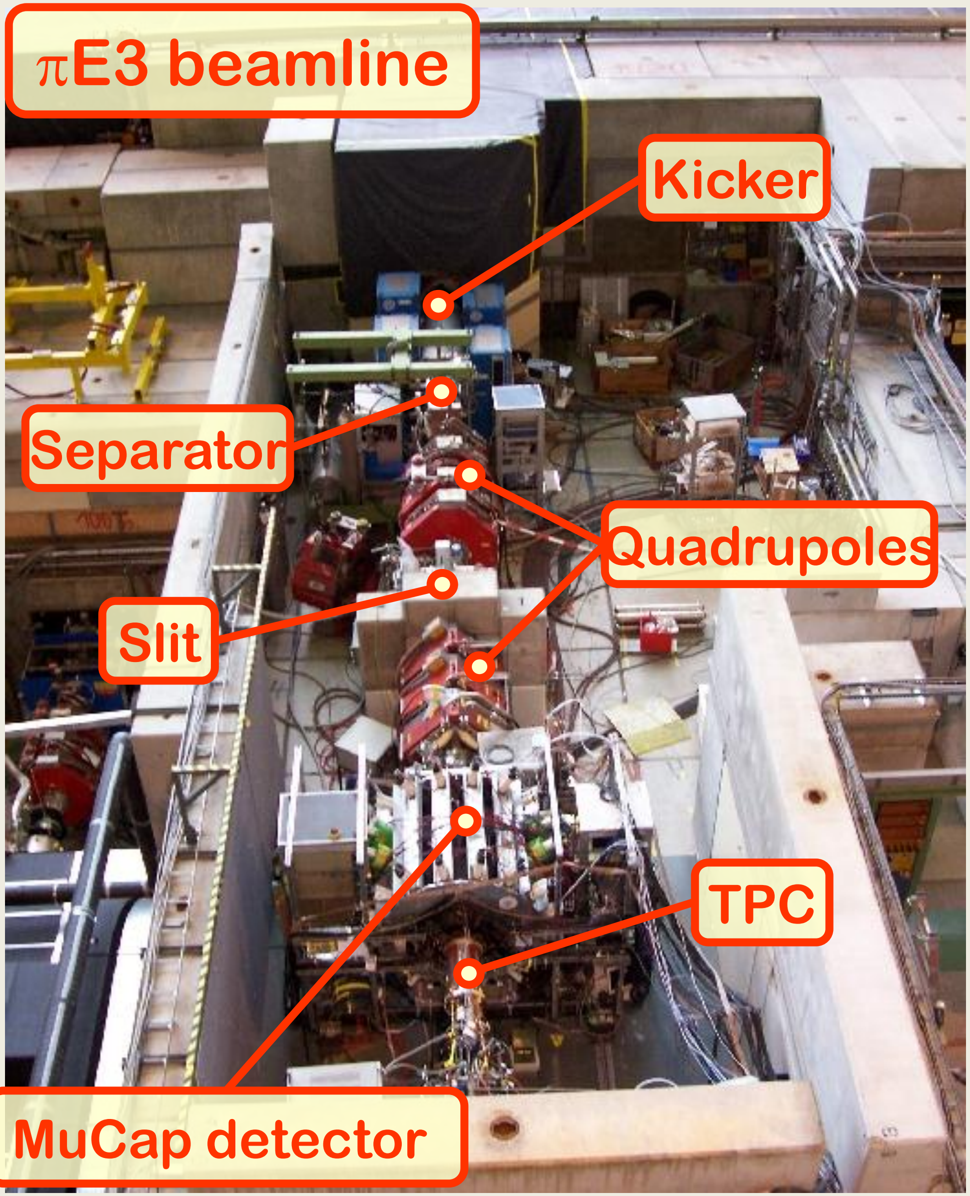


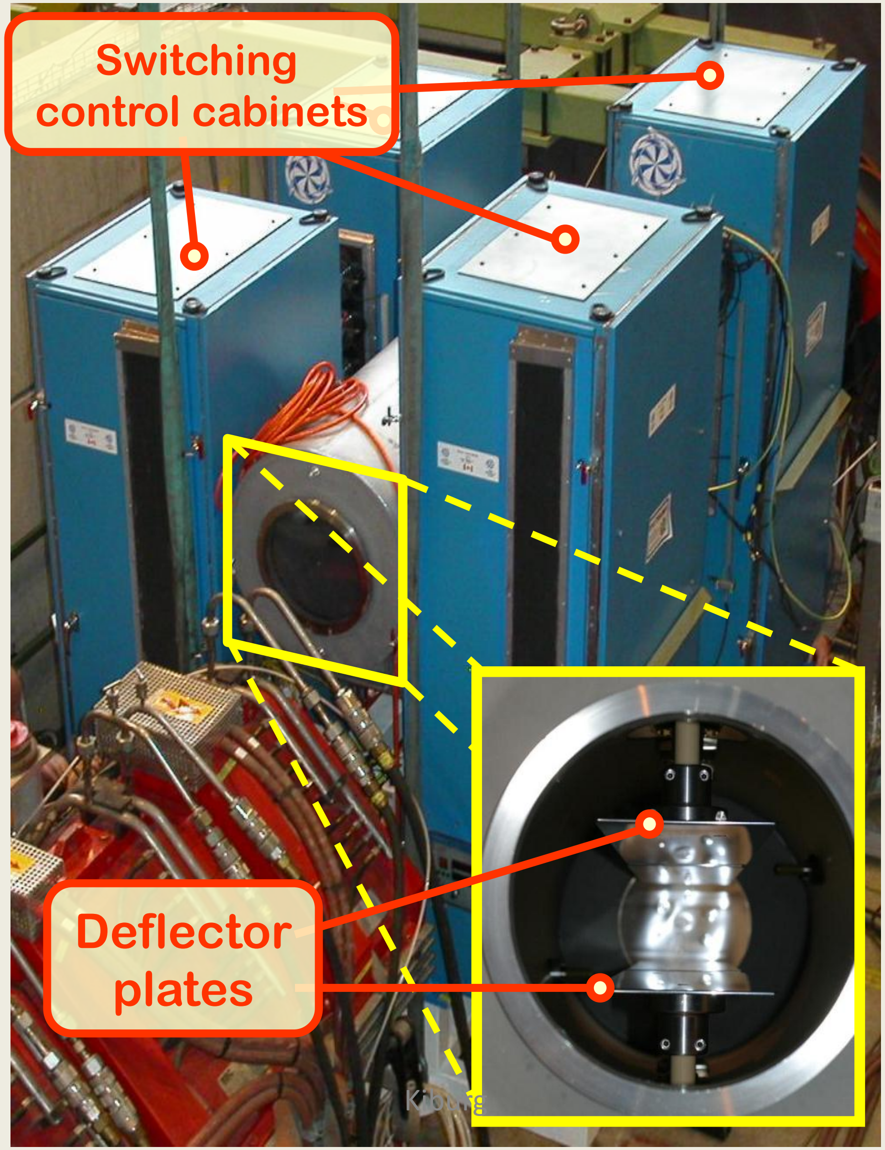




πE3 Beamline,
Paul Scherrer Institut,
Villigen, Switzerland

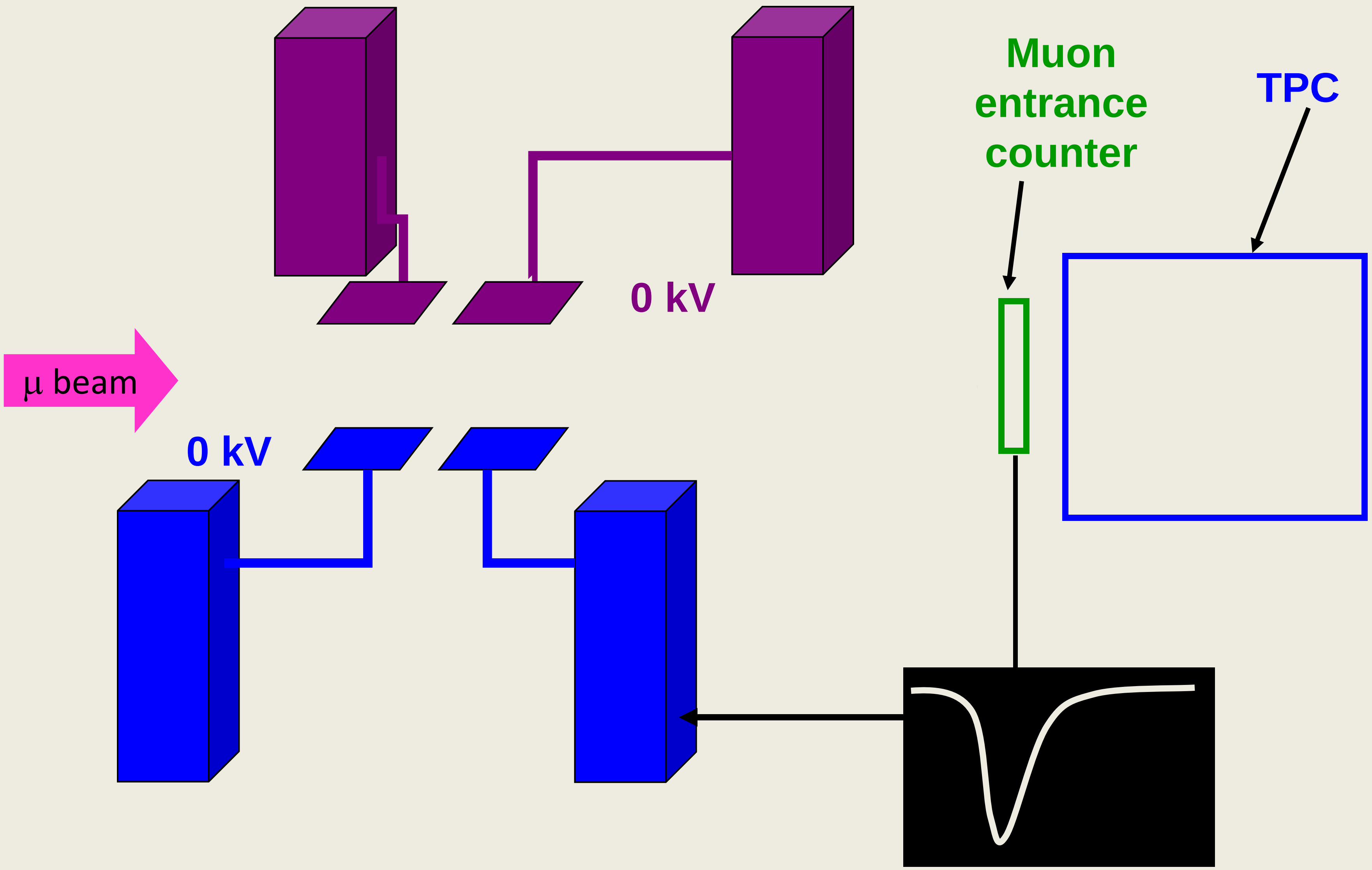
The experiment is conducted in the πE3 beamline at PSI



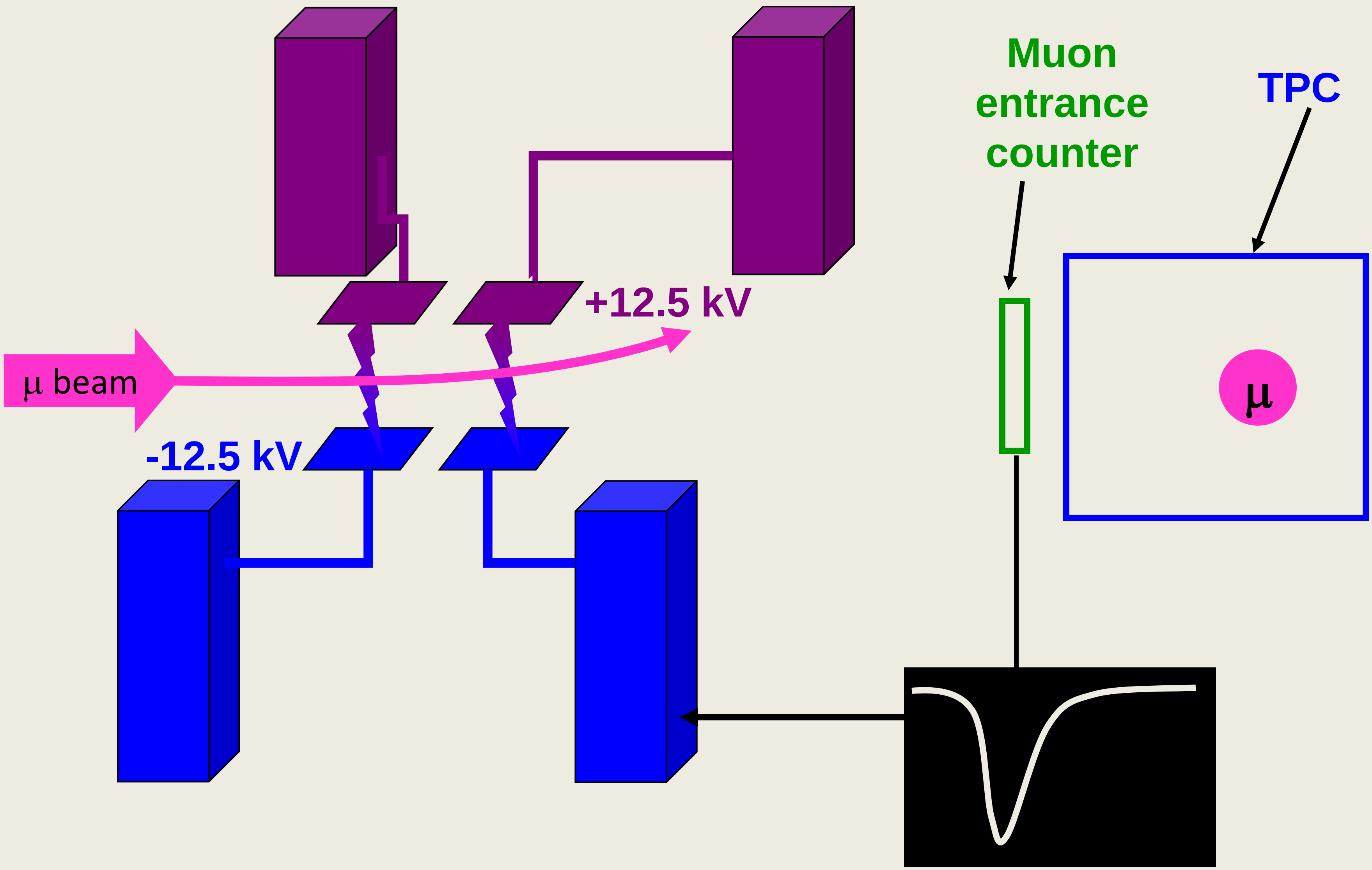


- Muon On Request

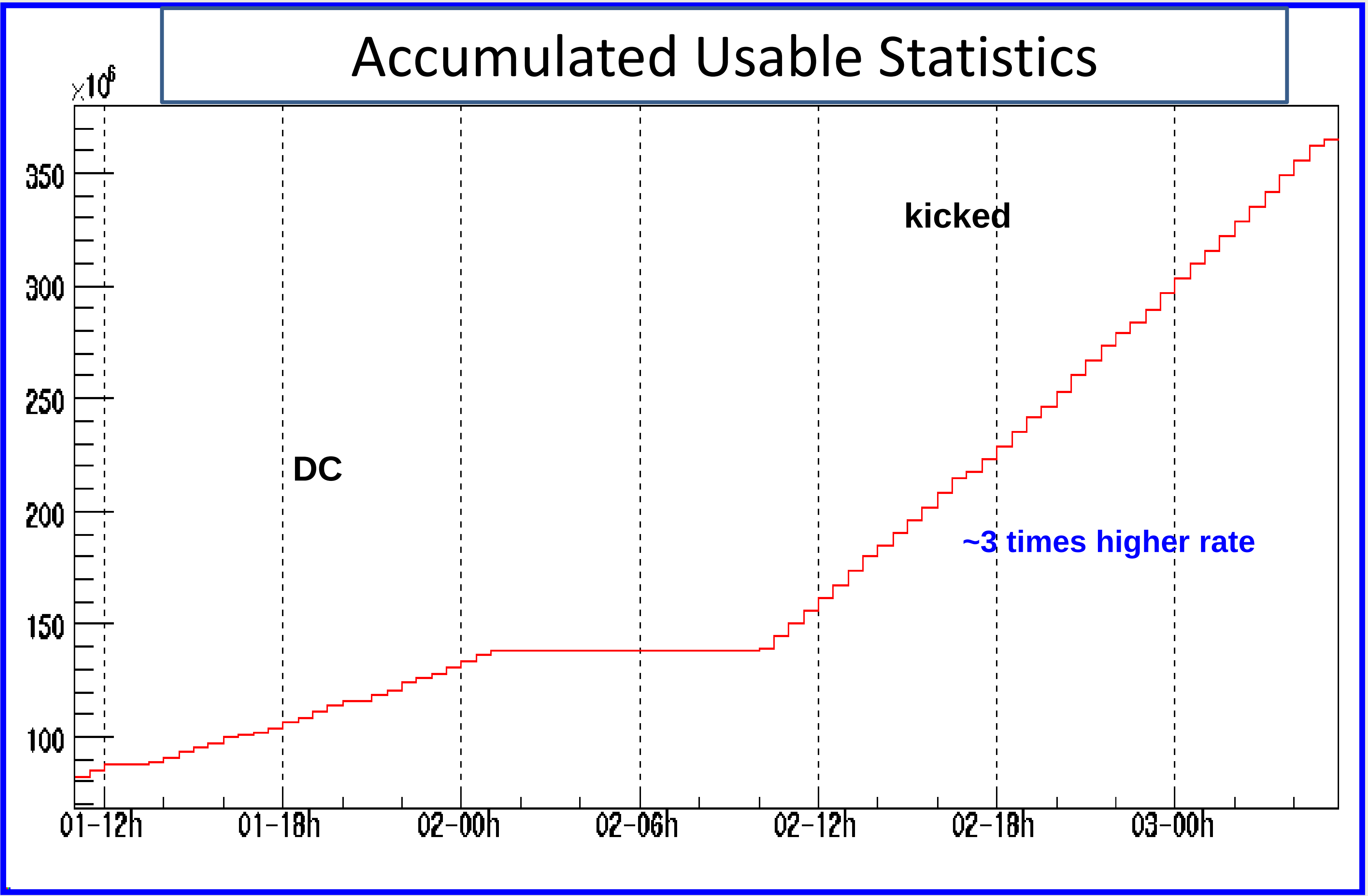
One muon at a time



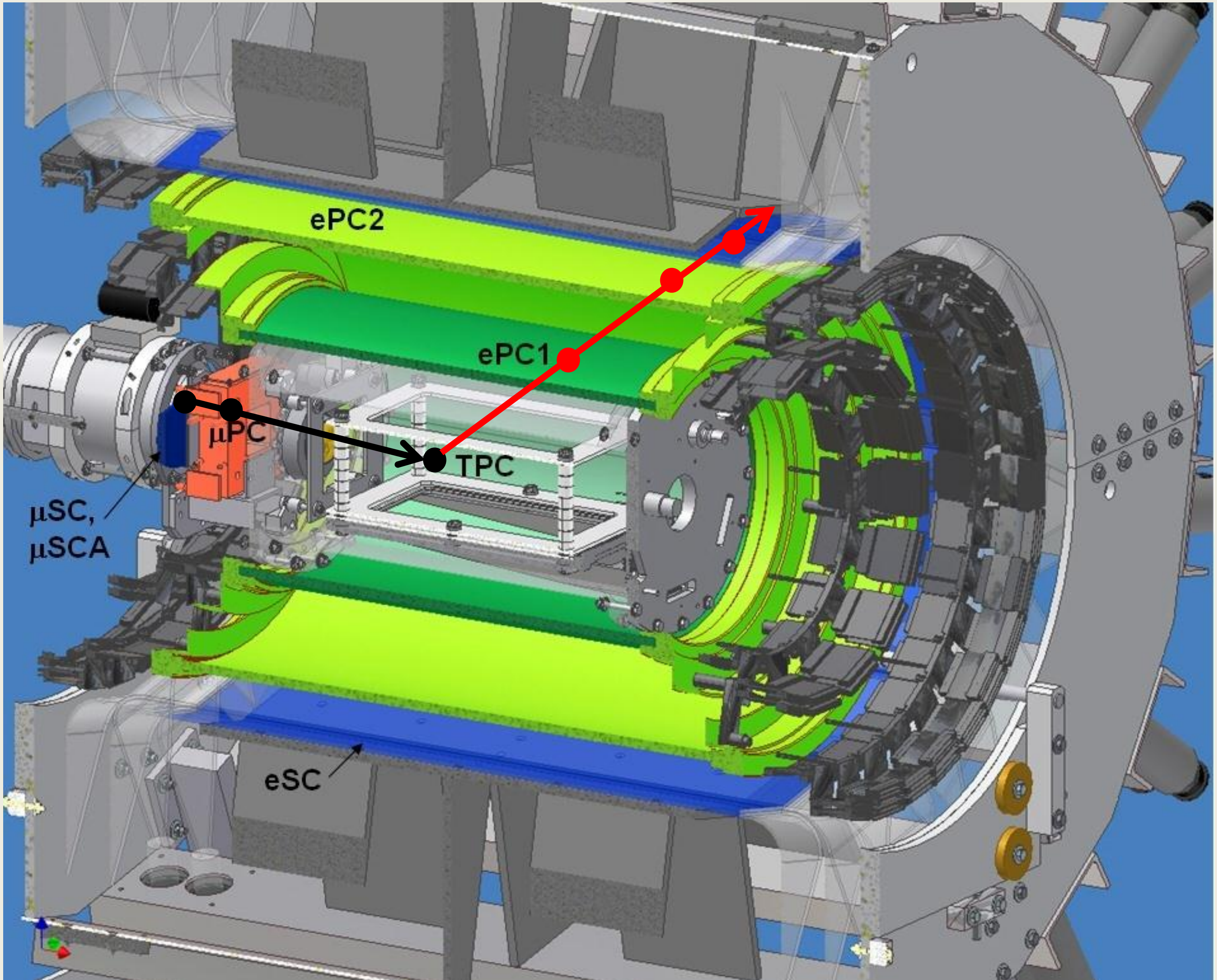
One muon at a time

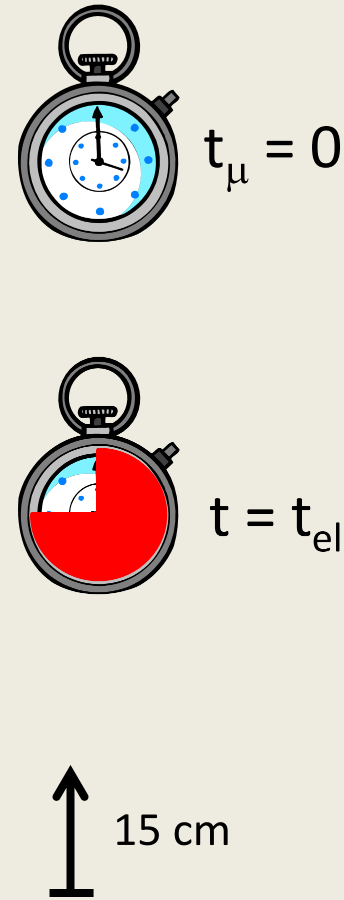


One muon at a time



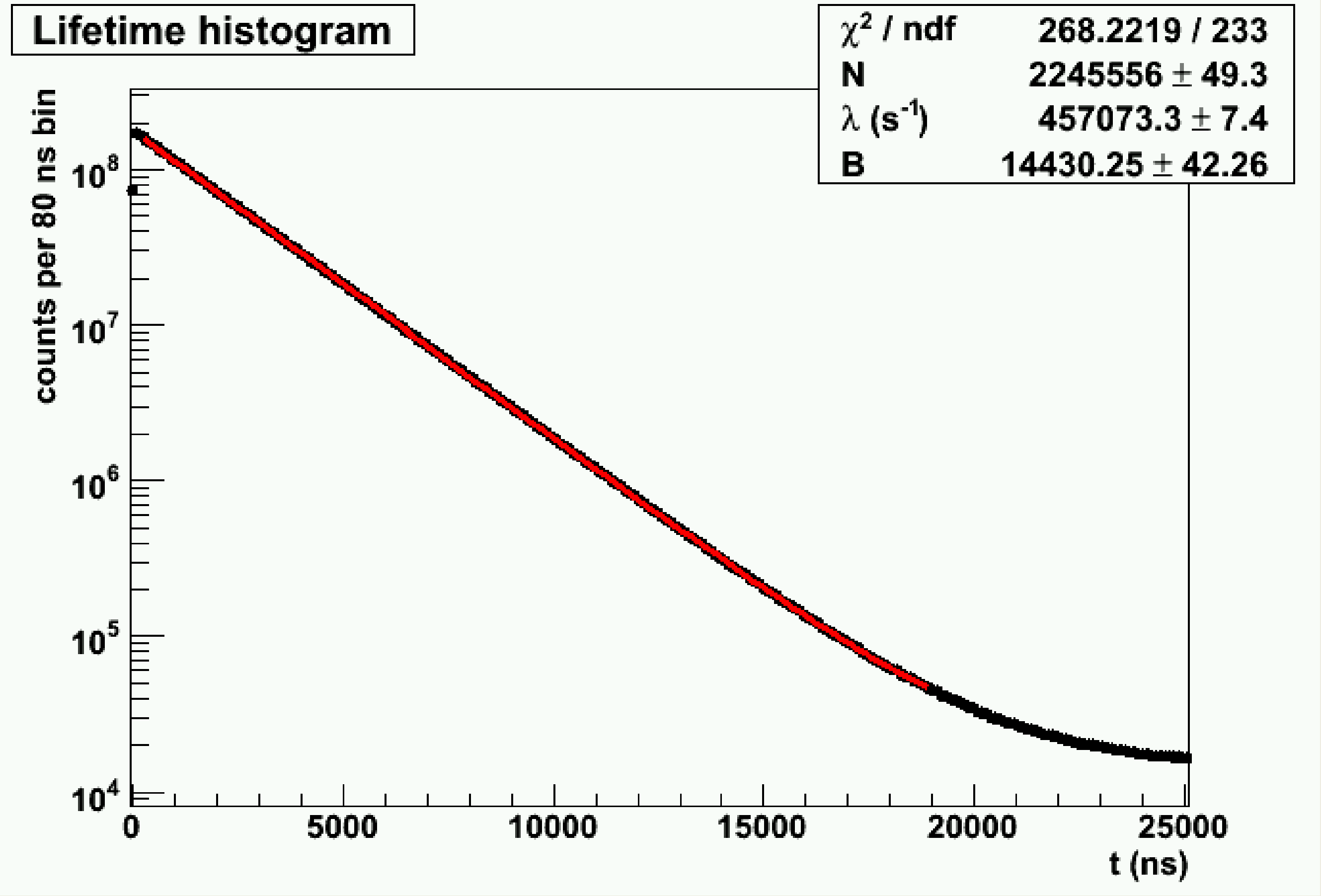
The MuCap Detector



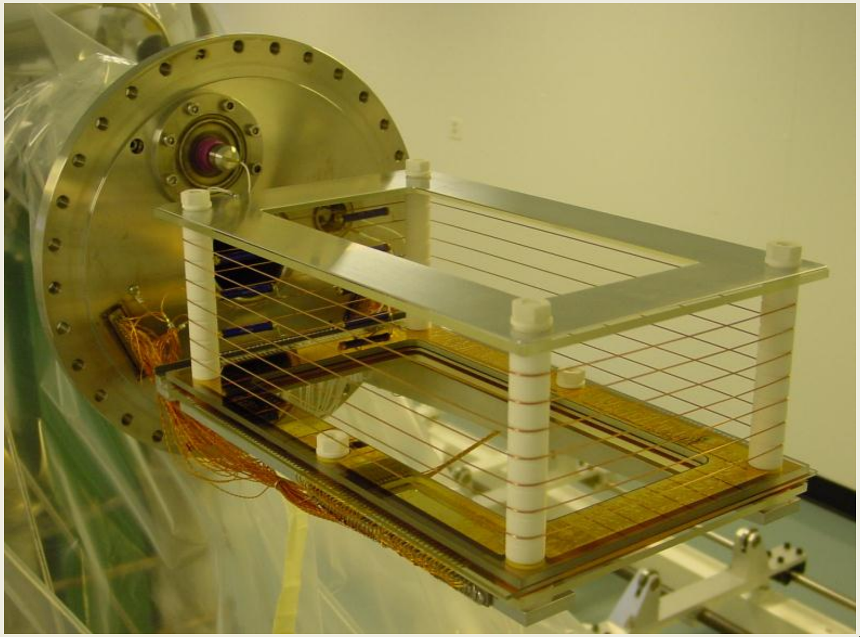


The decay time is histogrammed and fit with an exponential plus background

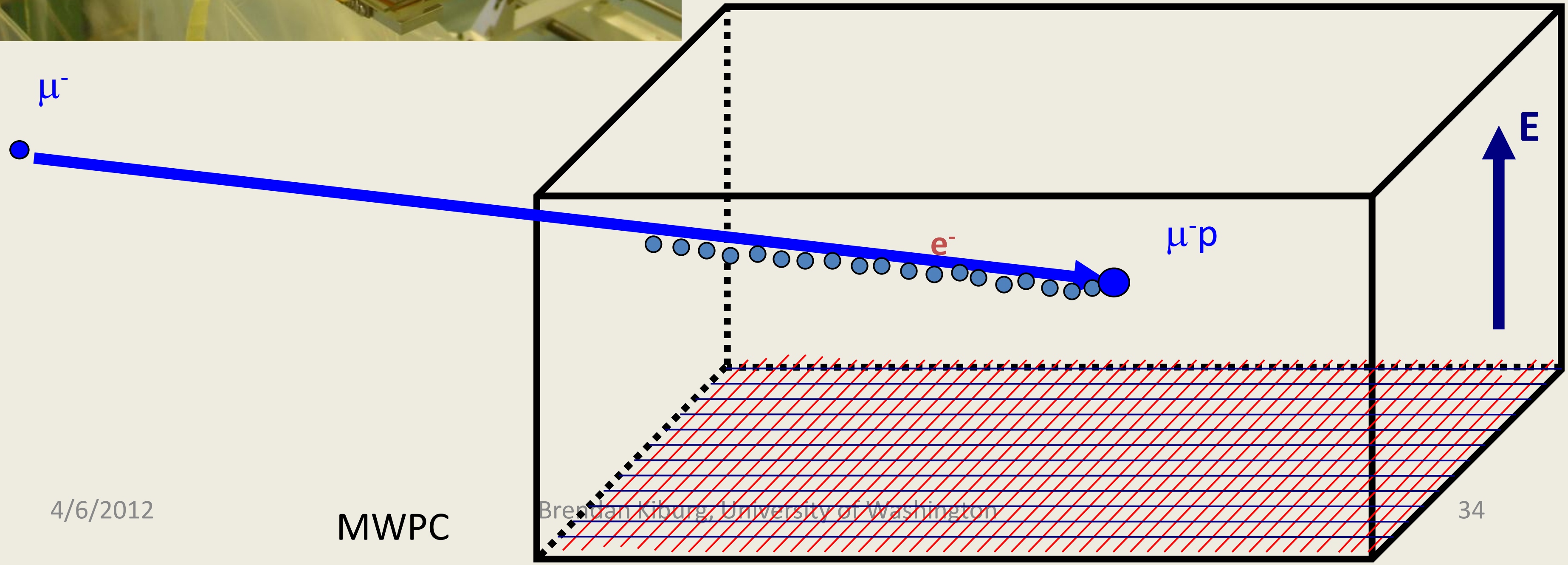
$$N(t) = N_0 \cdot w \cdot \lambda \cdot e^{(-\lambda t)} + B$$



The TPC images the muon stop



- 10 bar ultra-pure H_2
- Bakeable glass/ceramic materials
- No materials in the fiducial volume



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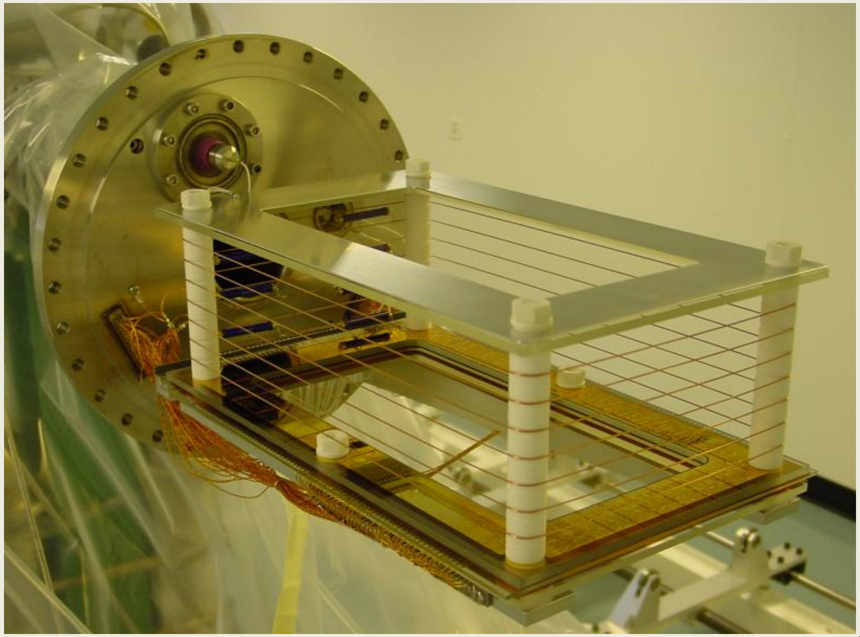

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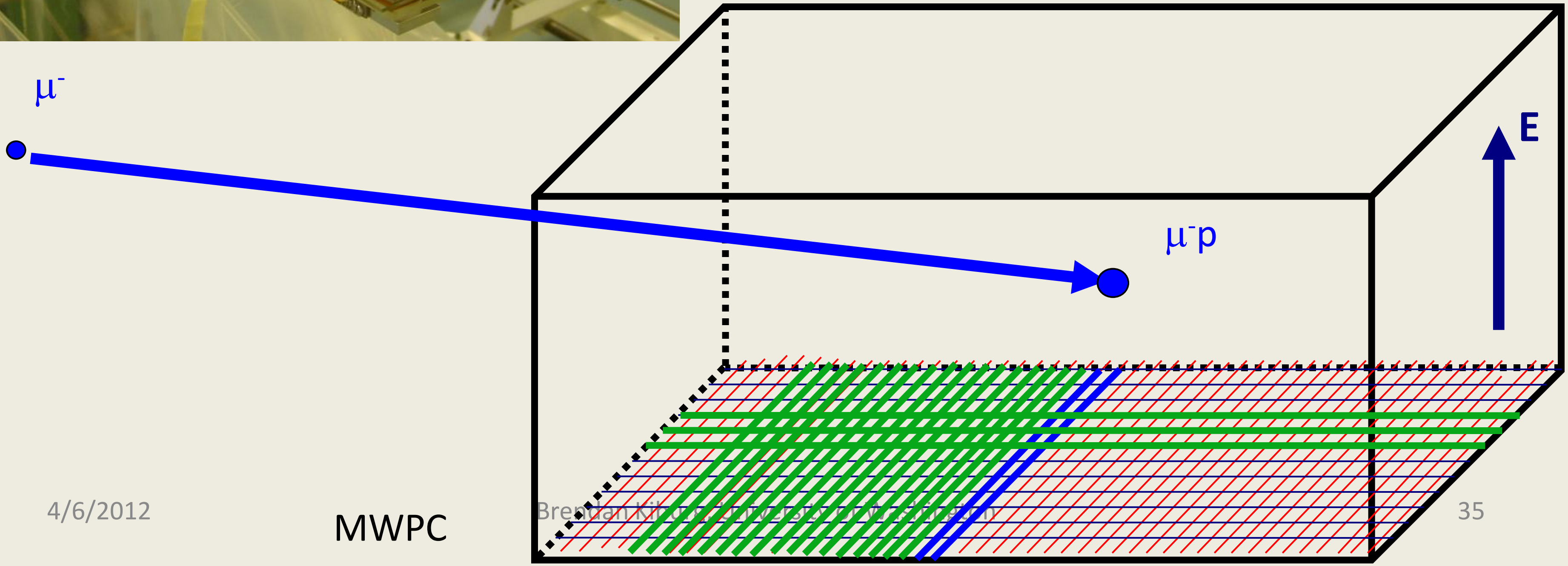
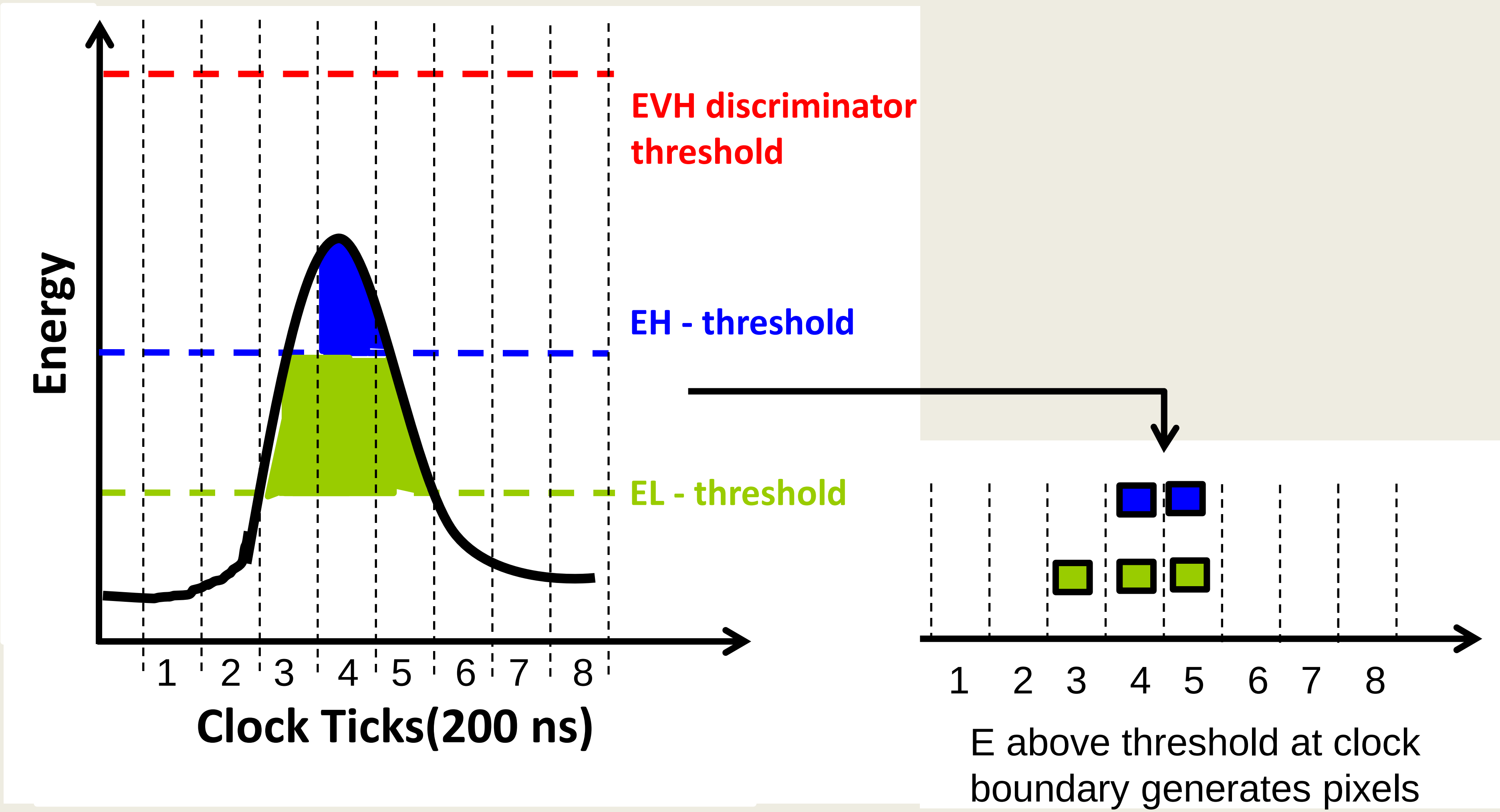
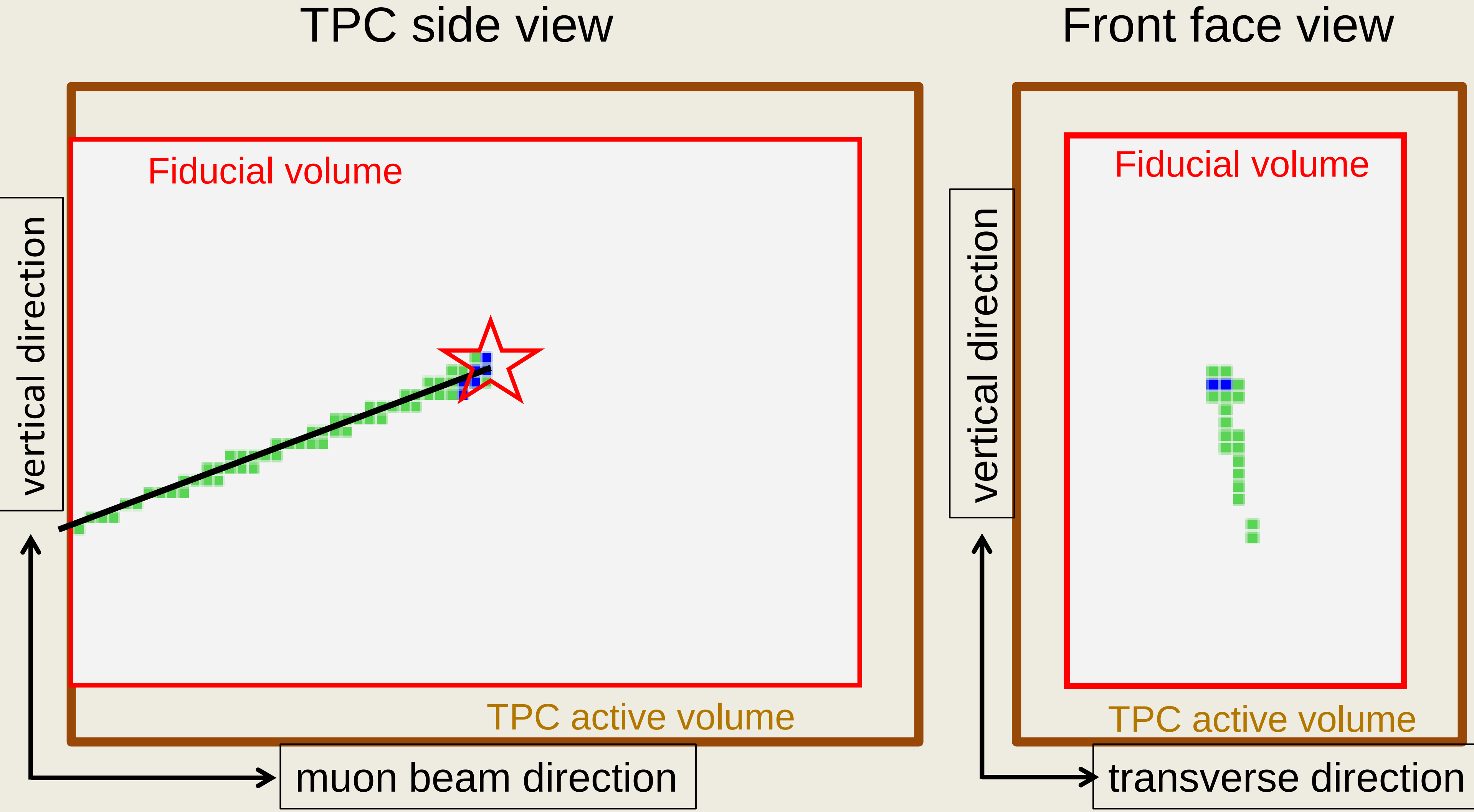


The collection of charge on anode wires generates pulses, which are digitized into pixels

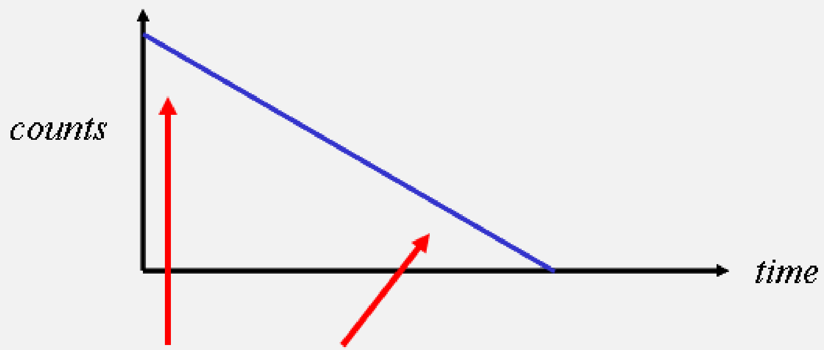


A sample event



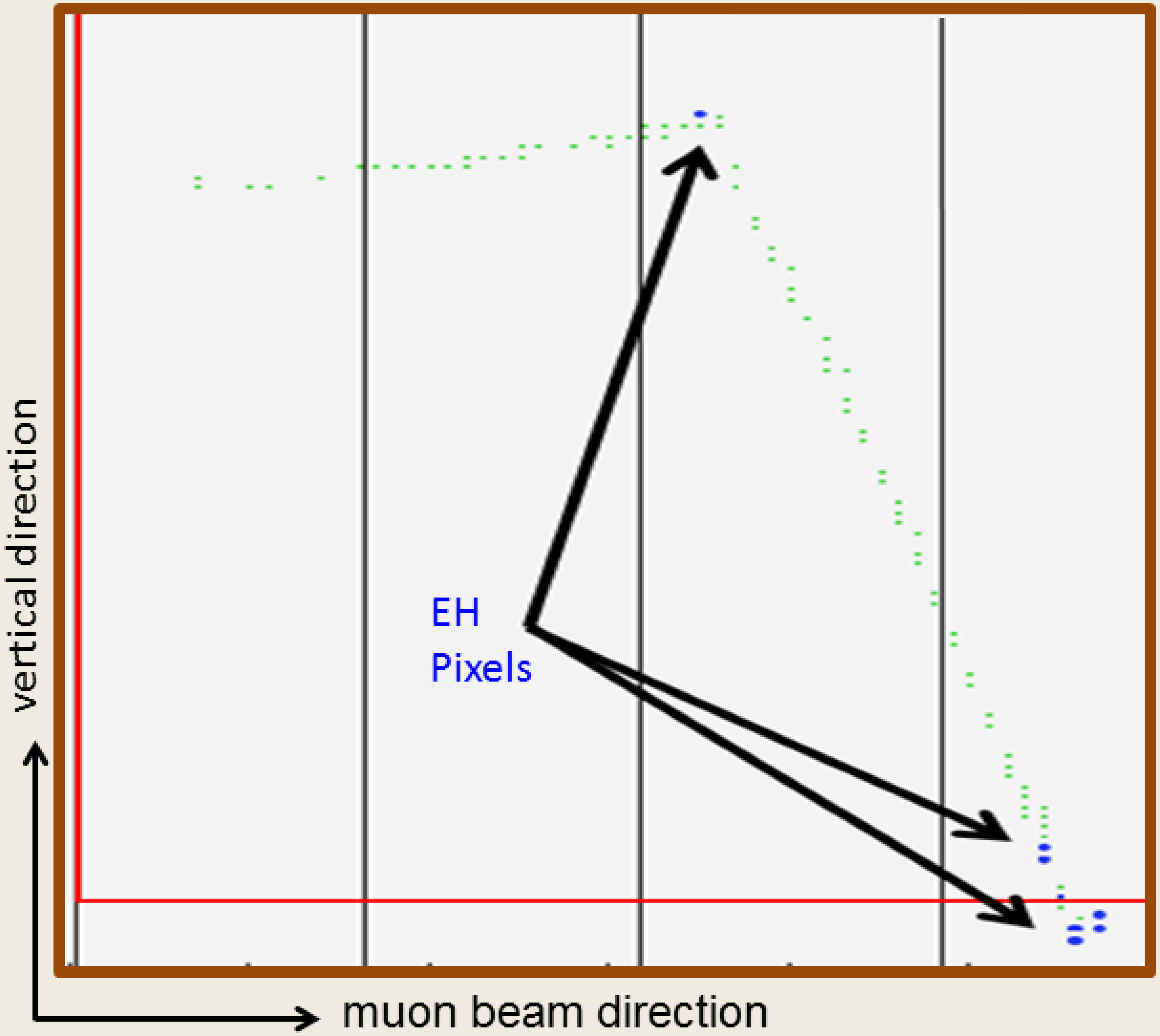
How can we get the capture rate wrong?

- Acceptance of events that fake a good stop, but actually stop in other materials



- Any “early-to-late” changes in muon acceptance
  - If the decay electron changes the probability that we identify the muon stop as “good” in a time-dependent way

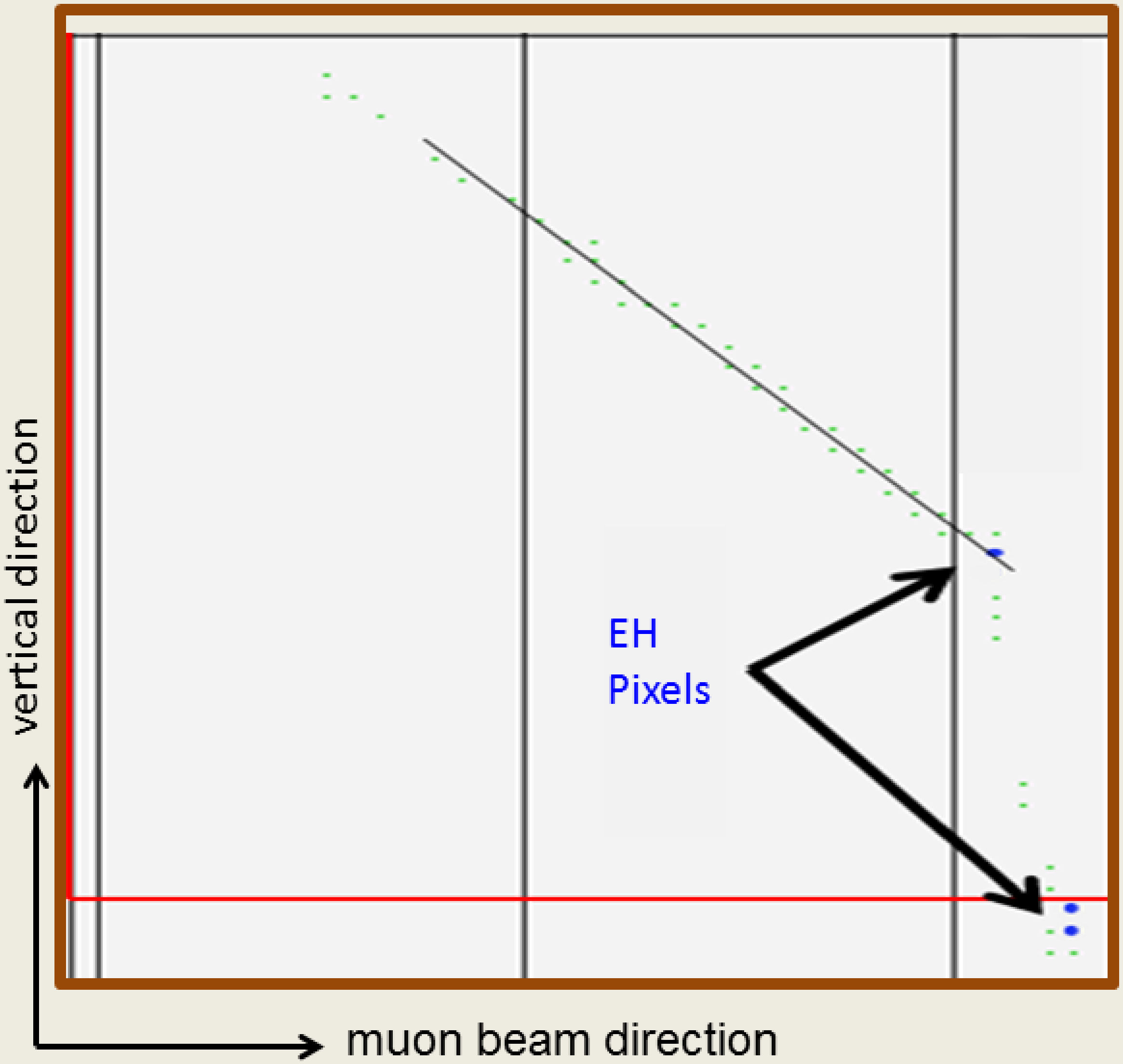
Muons that fake a stop in the fiducial volume but actually stop in the surrounding high-Z materials are dangerous



Muon leaves Fiducial Vol

And probably Active Vol

The scatter events are not always so clear…

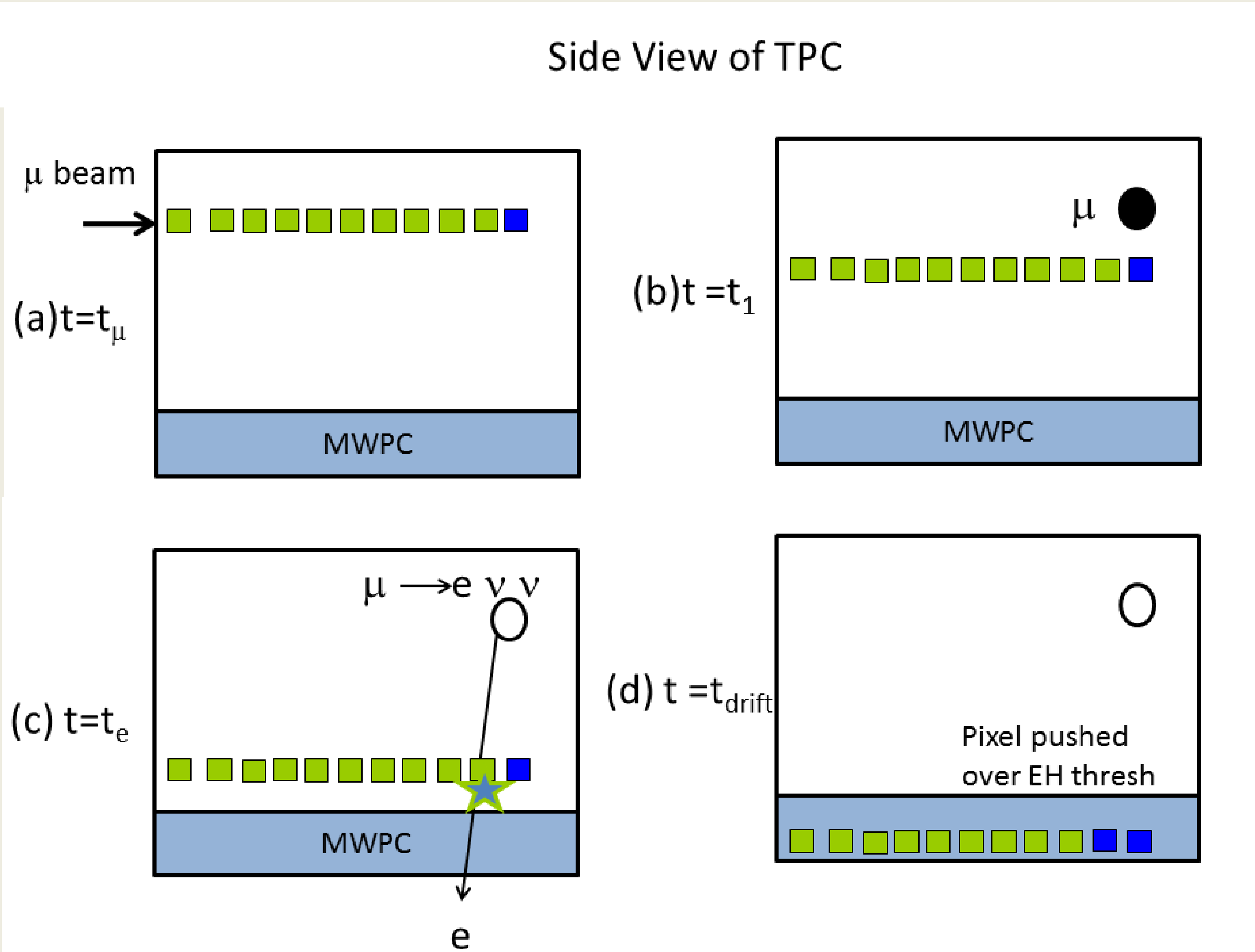


- Recoil proton from scatter
- Deposit energy on 1 anode
- Require > 1 blue pixels to eliminate scatters

Muon leaves Fiducial Vol

And probably Active Vol

Energy deposition from decay electrons can modify pixels in a muon track



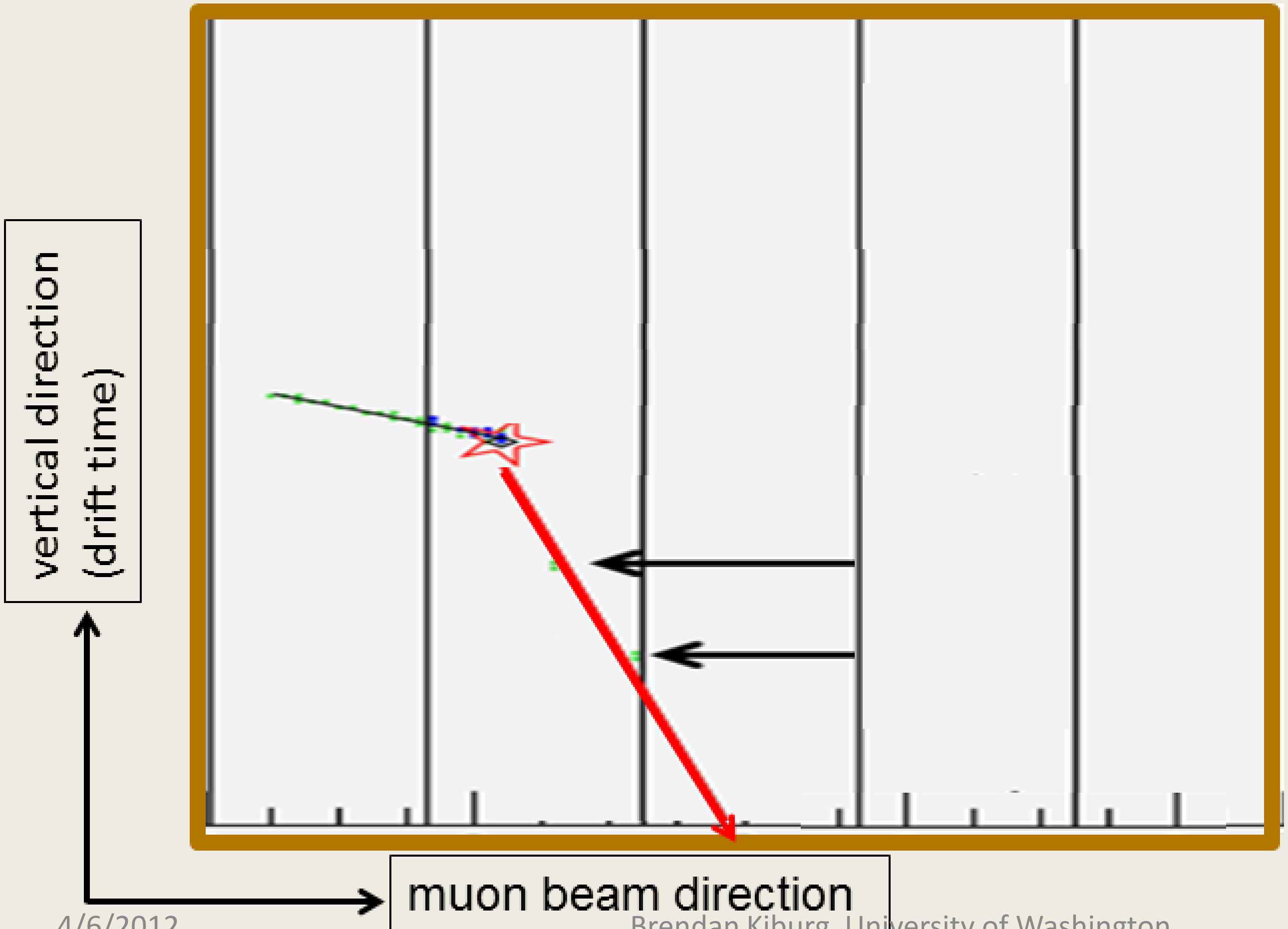
(a) μ enters TPC & Ionizes gas

(b) Charge drifts towards MWPC

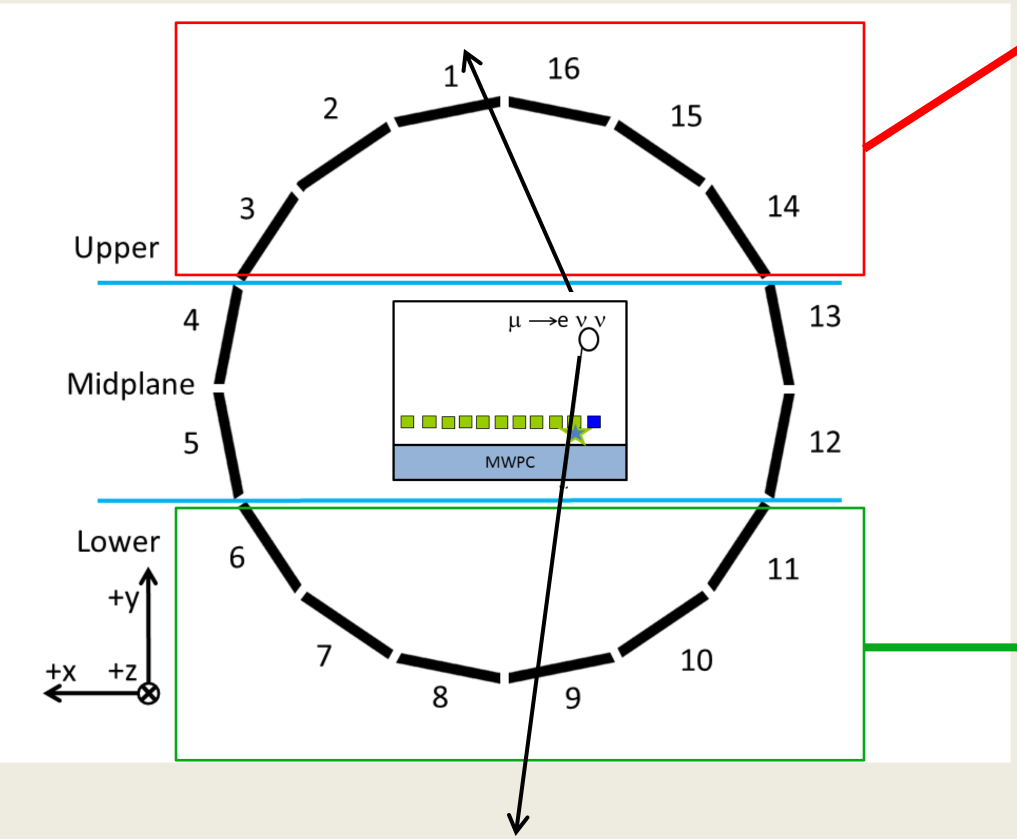
(c) Decay electron deposits energy

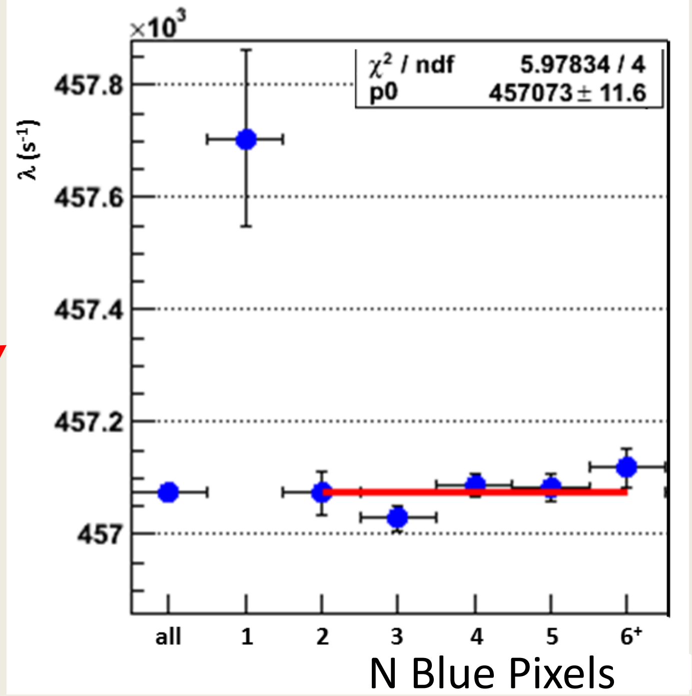
(d) Augments pixels

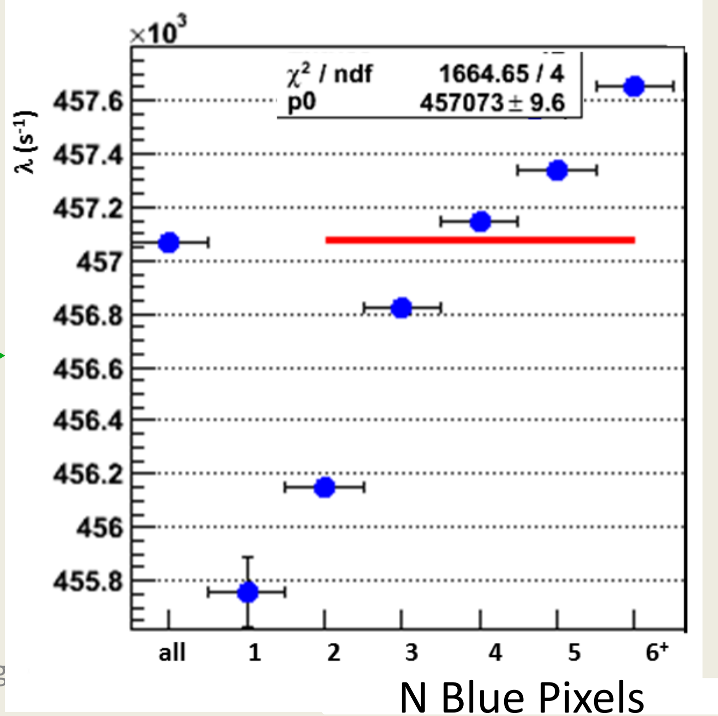
Pixels can be generated by the electron



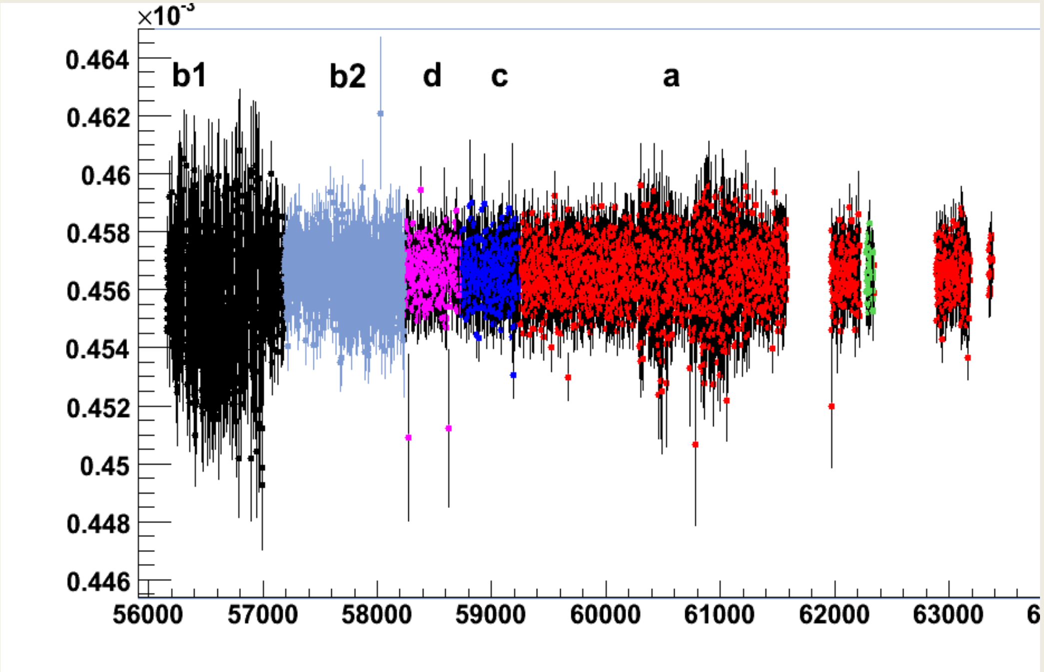
The interference is time- and space-dependent



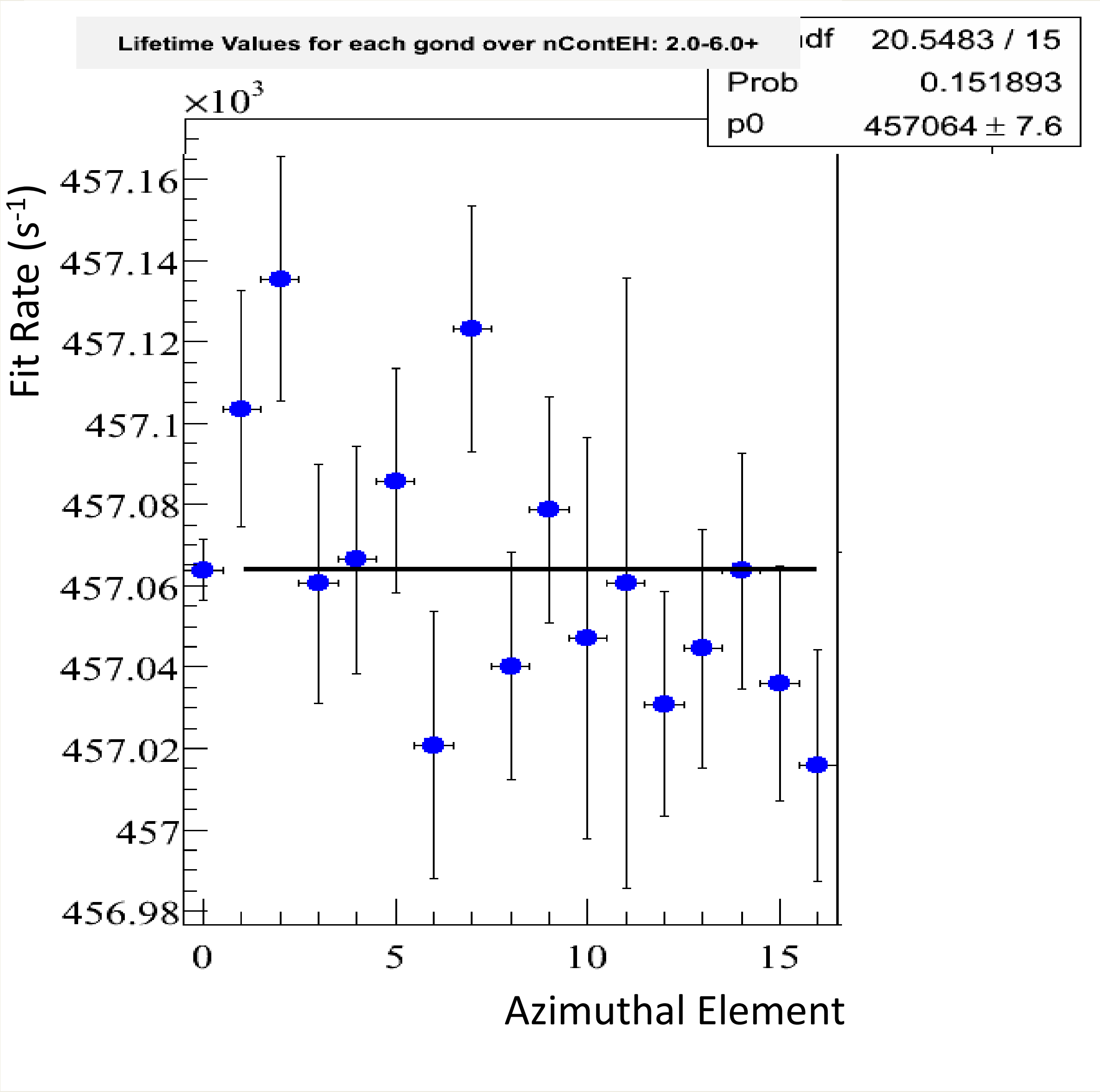




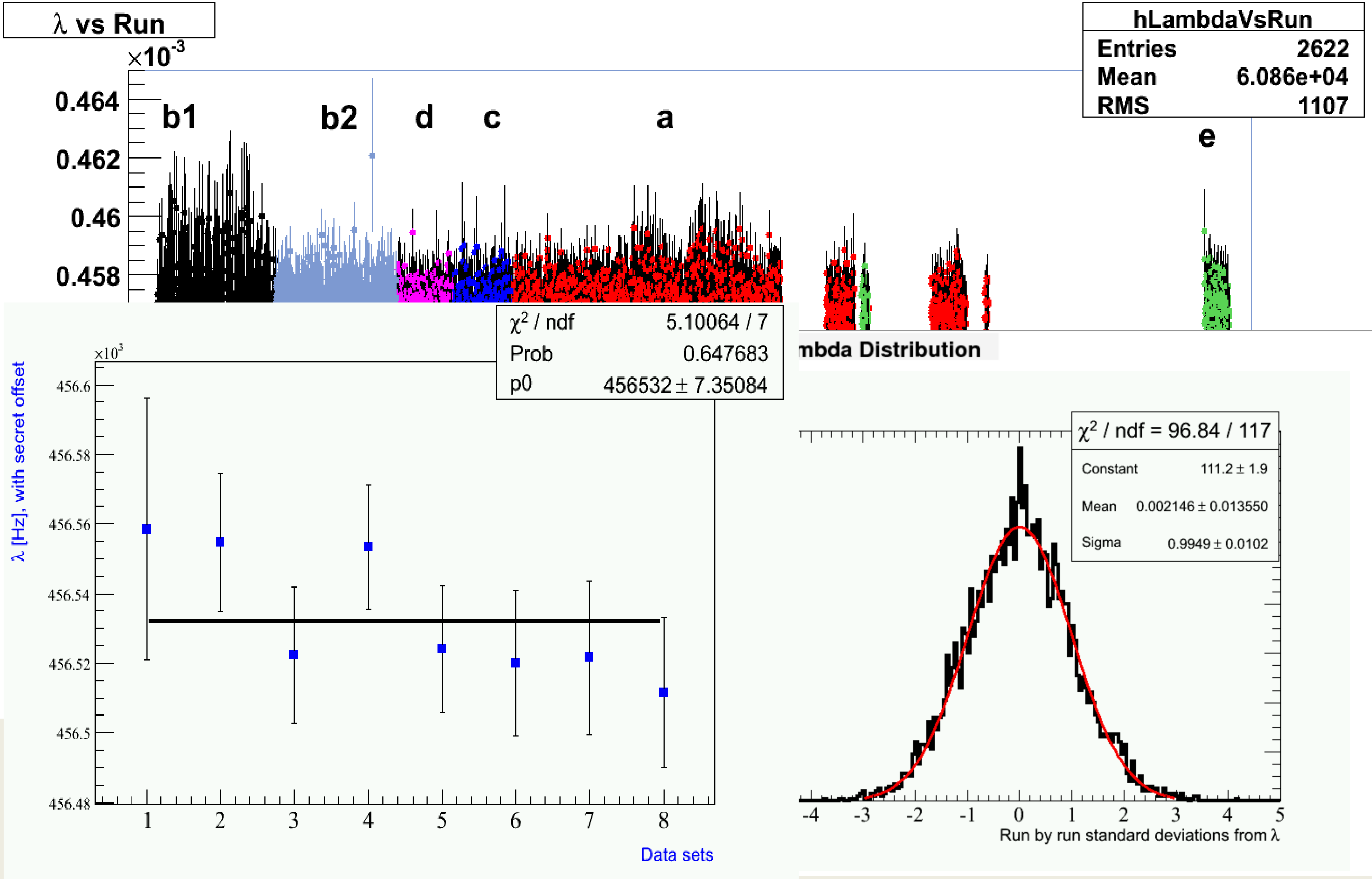
Consistency Checks



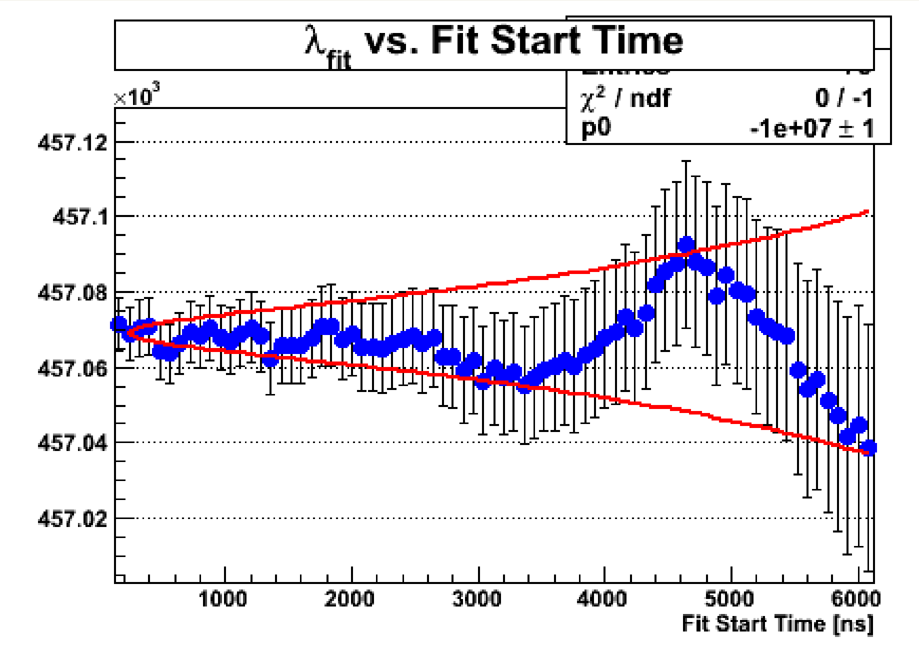
The disappearance rate is independent of azimuth

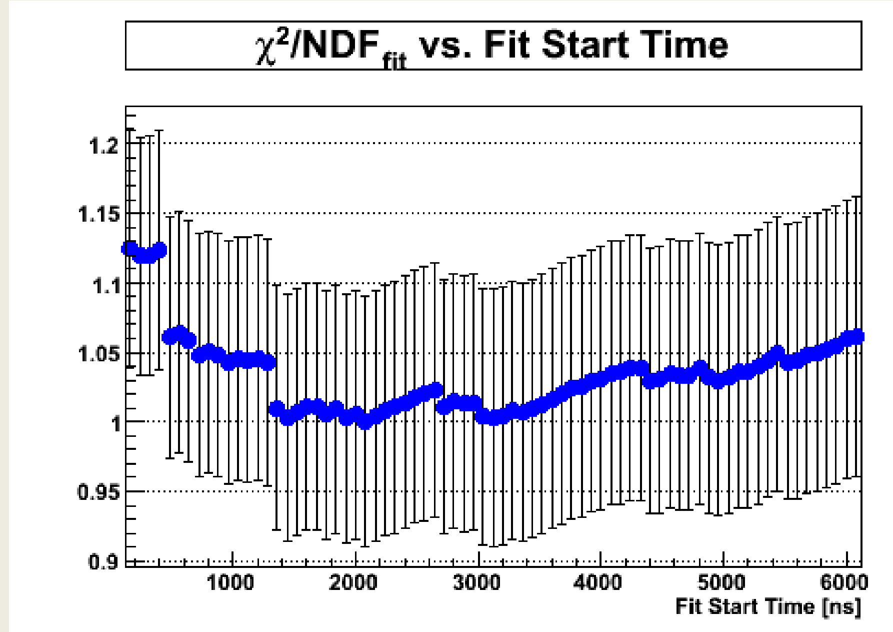


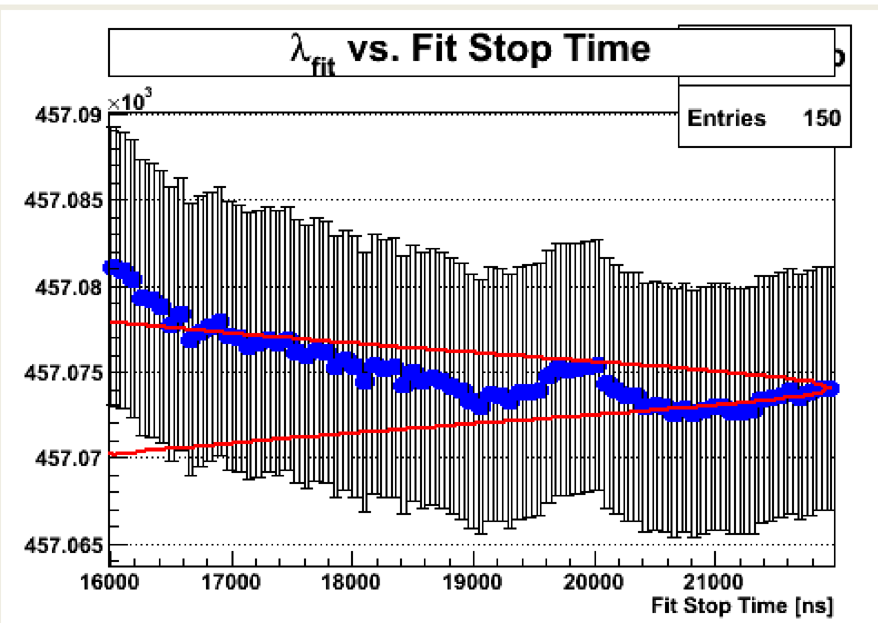
The disappearance rate is independent of run number

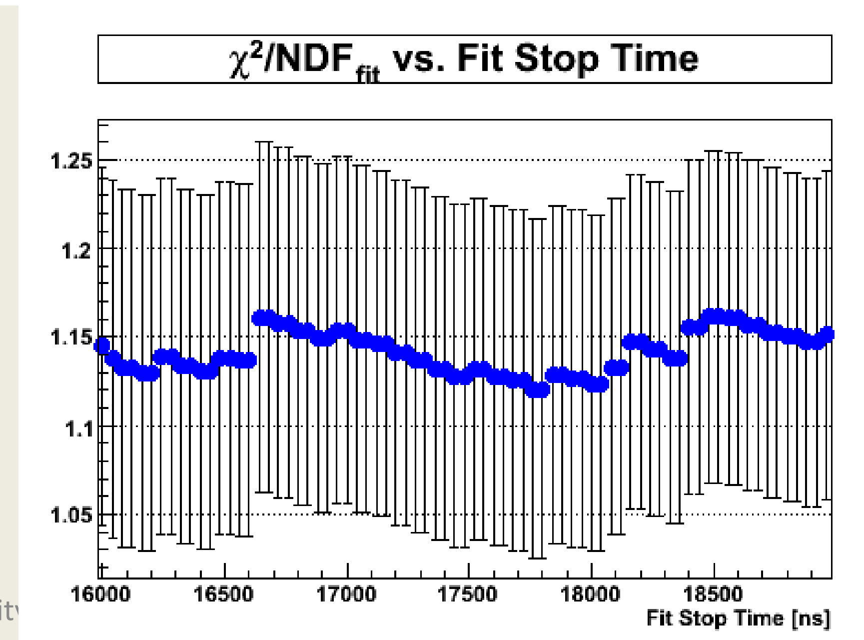


Start and stop-time-scans demonstrate consistency

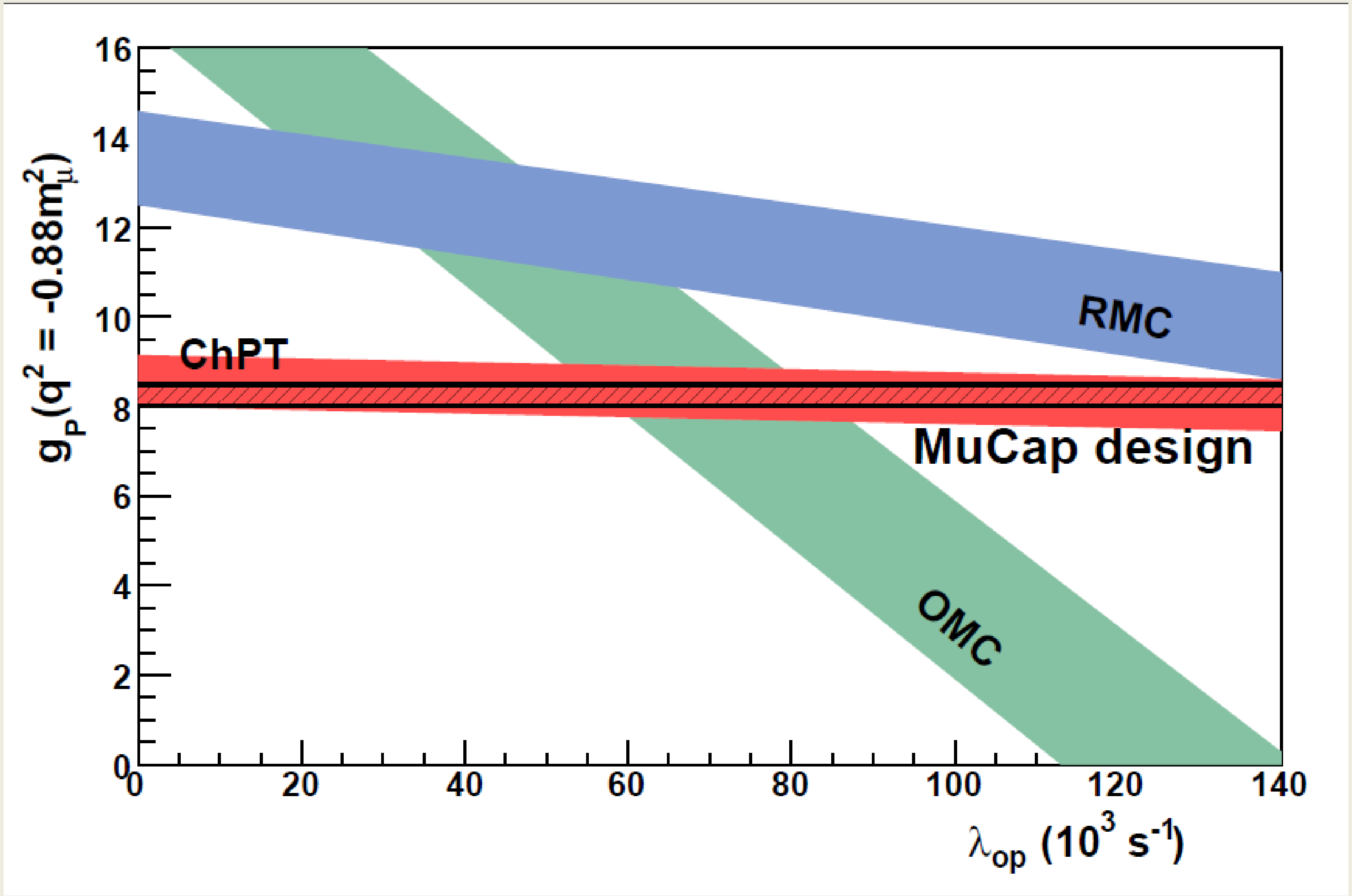








Results



ChPT
RMC
MuCap design
OMC
$g_P(q^2 = -0.88m_\mu^2)$
λ_{op} (10^3 s^{-1})
0
2
4
6
8
10
12
14
16
0
20
40
60
80
100
120
140

10 times increased statistics

Year	Statistics [10^{10} muon decays]		Comment
	μ-	μ+	
2004	0.16	0.05	published *
2006	0.55	0.16	This talk
2007	0.50	0.40	This talk
Total	**~1.21**	**~0.61**	**~60TB raw data**

*V.A. Andreev et al., Phys. Rev. Lett. 99, 03202 (2007)

Remember: λ^+ known to 1 ppm from MuLan!

Double Blinded measurement

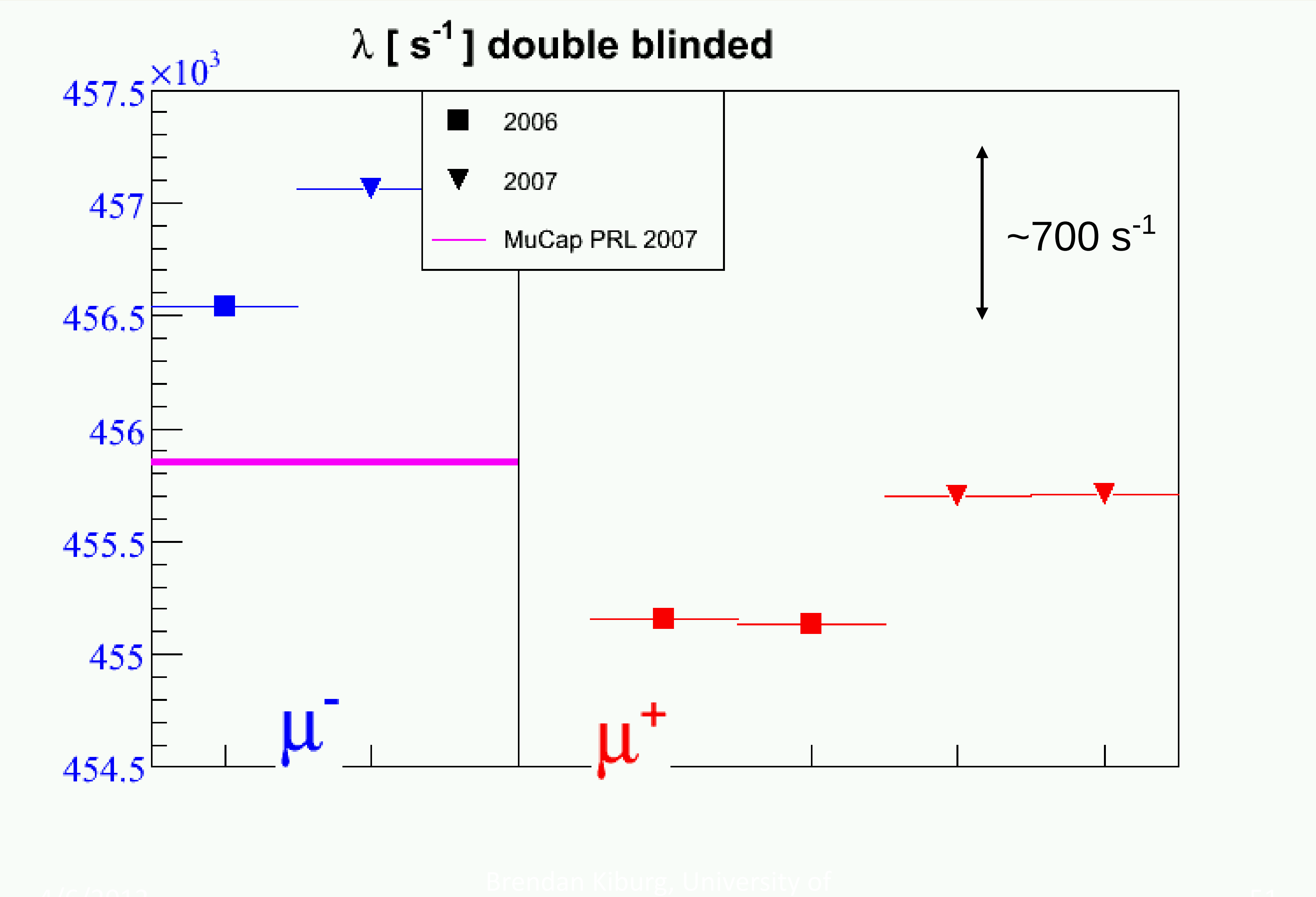
500 MHz precise master clock

Detune clock

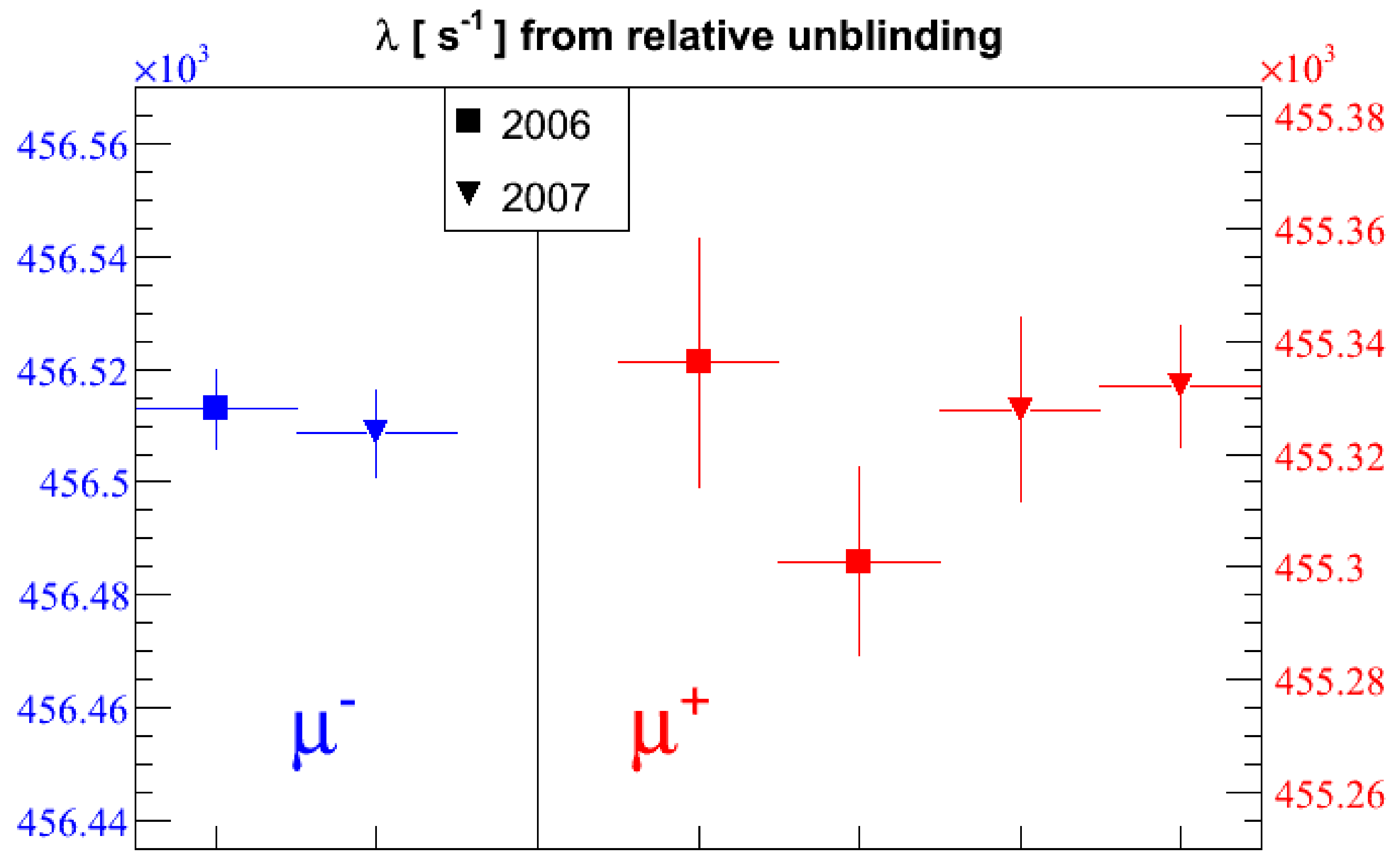
Hide from analyzers

Analyzers add secret offset

Double blinded

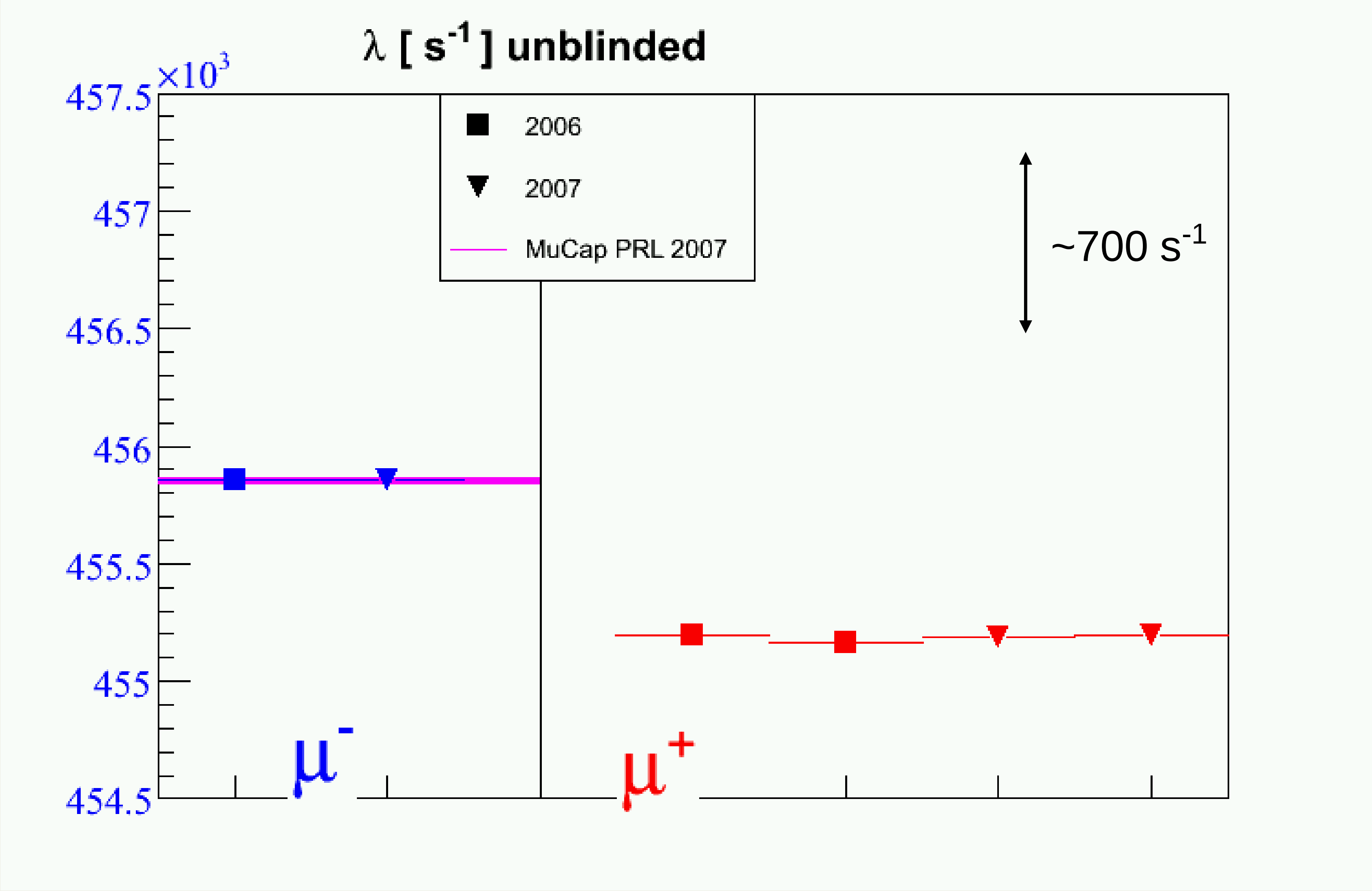


Relative unblinded



rates with secret offset, stat. errors only

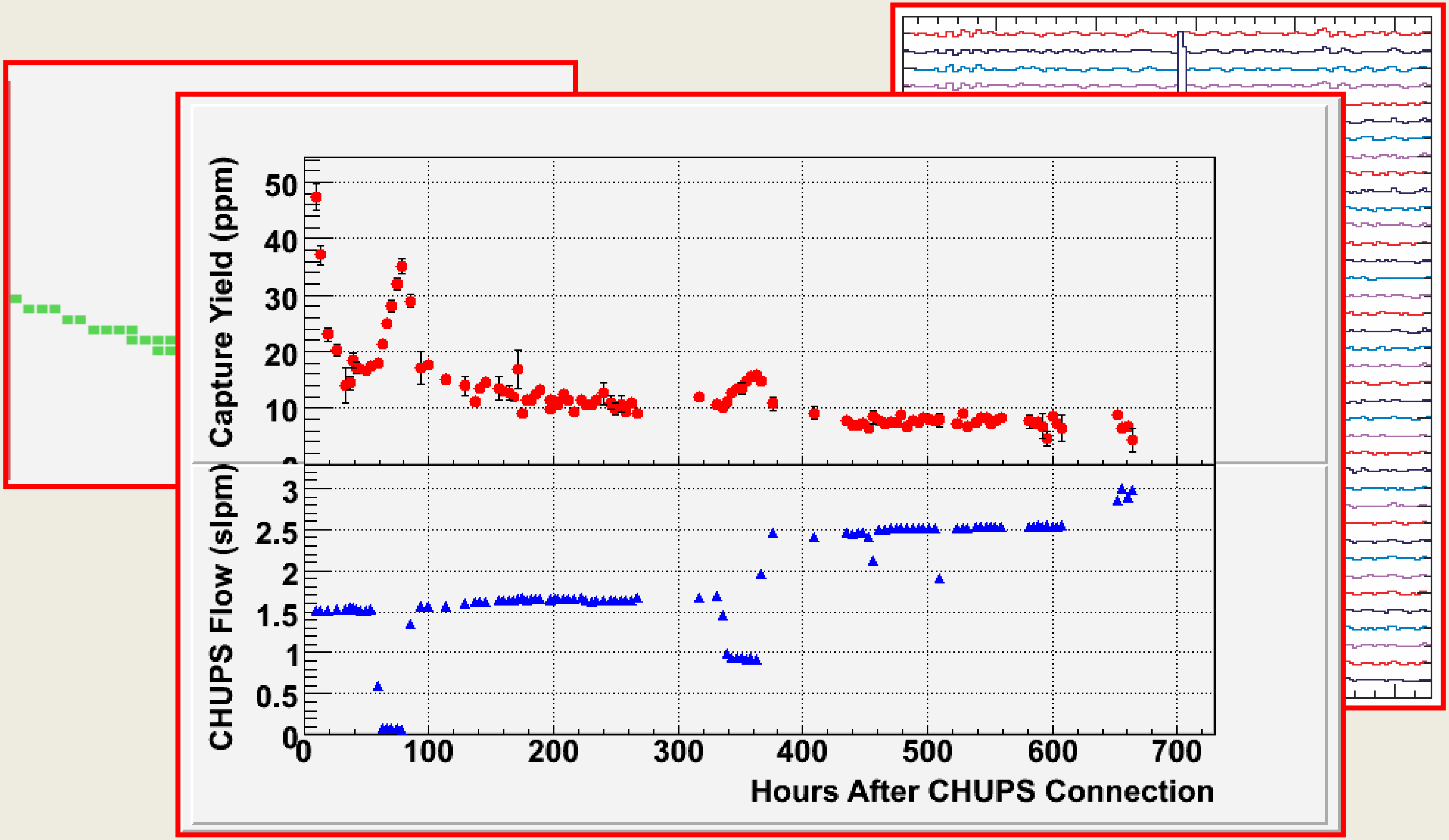
Fully Unblinded



Systematic corrections and errors

Systematic errors	Run 2006		Run 2007		Comment
	λ (s^{-1})	$\delta\lambda$ (s^{-1})	λ (s^{-1})	$\delta\lambda$ (s^{-1})	
High-Z impurities	-7.8	1.87	-4.54	0.93	
μp scatter	-12.4	3.22*	-7.20	1.25*	* = prelim.
μp diffusion	-3.1	0.1	-3.0	0.1	
Fiducial volume cut		3.0		3.0	
Entrance counter inefficiencies		0.5		0.5	
Choice of electron detector def.		1.8*		1.8*	* =prelim.
Total	**-23.3**	**5.14§**	**-14.74**	**3.88§**	§ = correlated

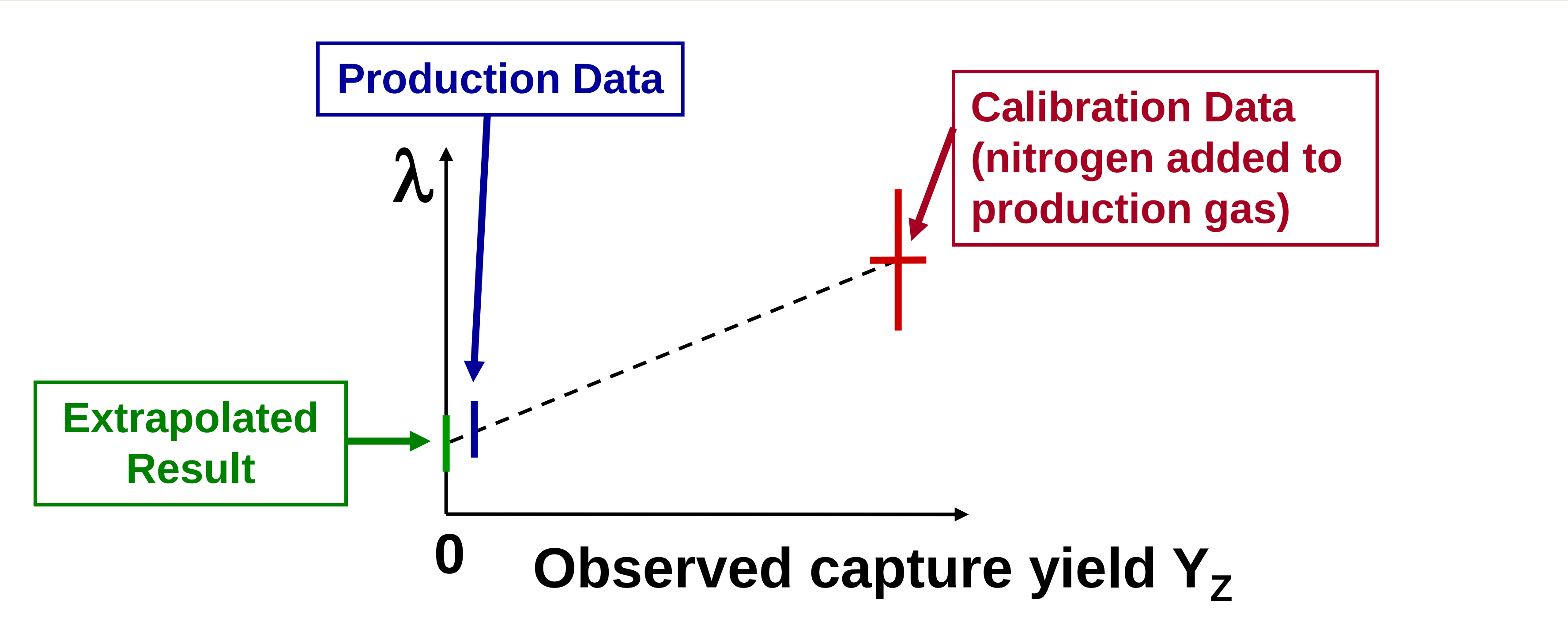
Impurity monitoring



2004 run: $c_N < 7$ ppb, $c_{H2O} \sim 30$ ppb

2006 / 2007 runs: $c_N < 7$ ppb, $c_{H2O} \sim 10$ ppb

Final high-Z impurity correction



Lifetime deviation is linear with the Z>1 capture yield.

External corrections to λ_

$$\lambda_\mu^- = \lambda_0 + \Lambda_S + \boxed{\Delta\lambda_{p\mu p}}$$

molecular formation

$$\lambda_\mu^+ + \boxed{\Delta\lambda_{\mu p}}$$

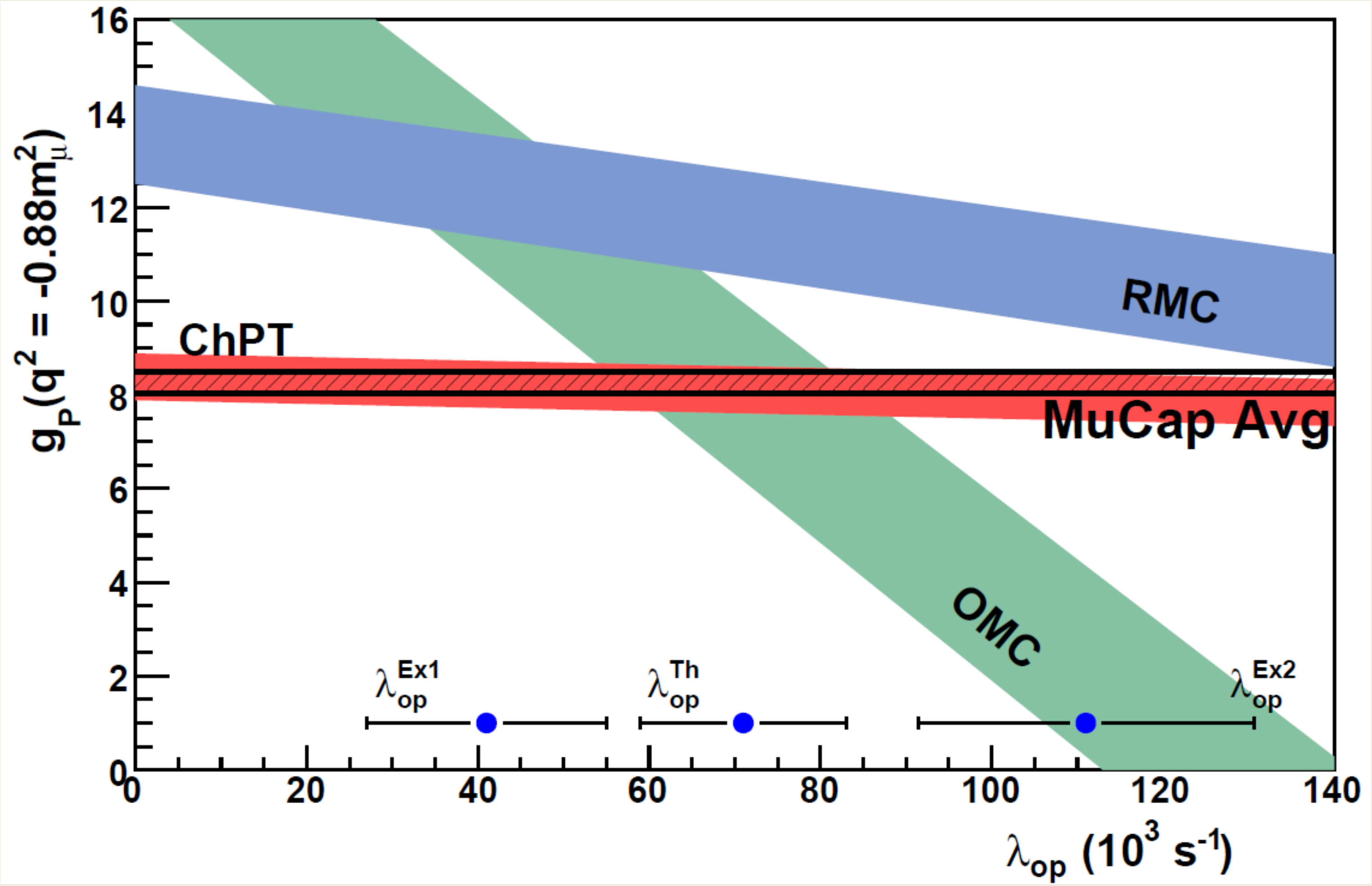
bound state effect

Λ_S (MuCap prelim.*) = $714.5 \pm 5.4_{stat} \pm 5.4_{syst}$ s^{-1}

* Small revision of molecular correction might affect $\Lambda_S < 0.5s^{-1}$ and syst. error

Λ_S (theory) = $711.5 \pm 3.5 \pm 3$ s^{-1}

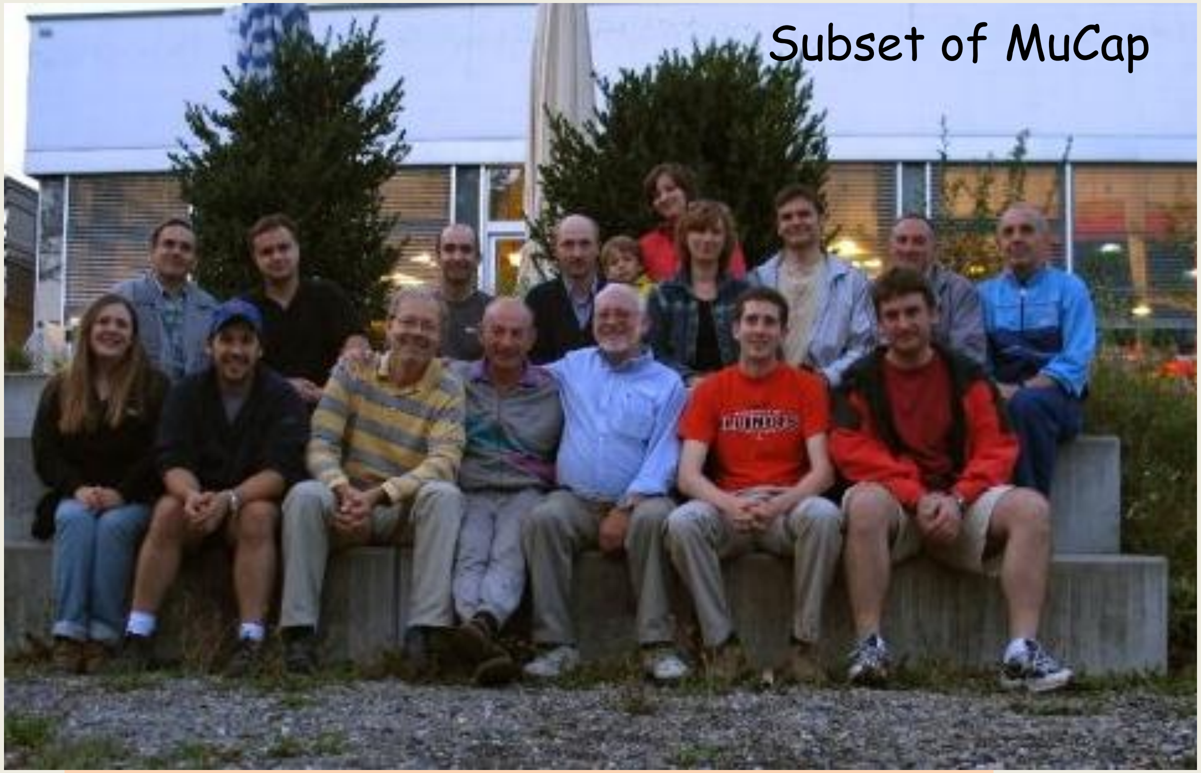
Precise and unambiguous MuCap result solves longstanding puzzle



$\boxed{g_P(\text{MuCap prelim.}) = 8.1 \pm 0.5}$

$g_P(\text{theory}) = 8.26 \pm 0.23$

Thank you!



V.A. Andreev, T.I. Banks, R.M. Carey, T.A. Case, D. Chitwood, S.M. Clayton, K.M. Crowe, J. Deutsch, J. Egger, S.J. Freedman, V.A. Ganzha, T. Gorringe, J. Govaerts, F.E. Gray, D.W. Hertzog, M. Hildebrandt, P. Kammel, B. Kiburg, S. Knaack, P. Kravtsov, A.G. Krivshich, B. Lauss, E.M. Maev, O.E. Maev, F. Mulhauser, C.S. Özben, C. Petitjean, G.E. Petrov, R. Prieels, G.N. Schapkin, G.G. Semenchuk, M. Soroka, V. Tichenko, A. Vasilyev, A.A. Vorobyov, M. Vznuzdaev, P. Winter

http://muon.npl.washington.edu/exp/MuCap/

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TU München, Garching, Germany
University of Kentucky, Lexington, USA
Boston University, USA

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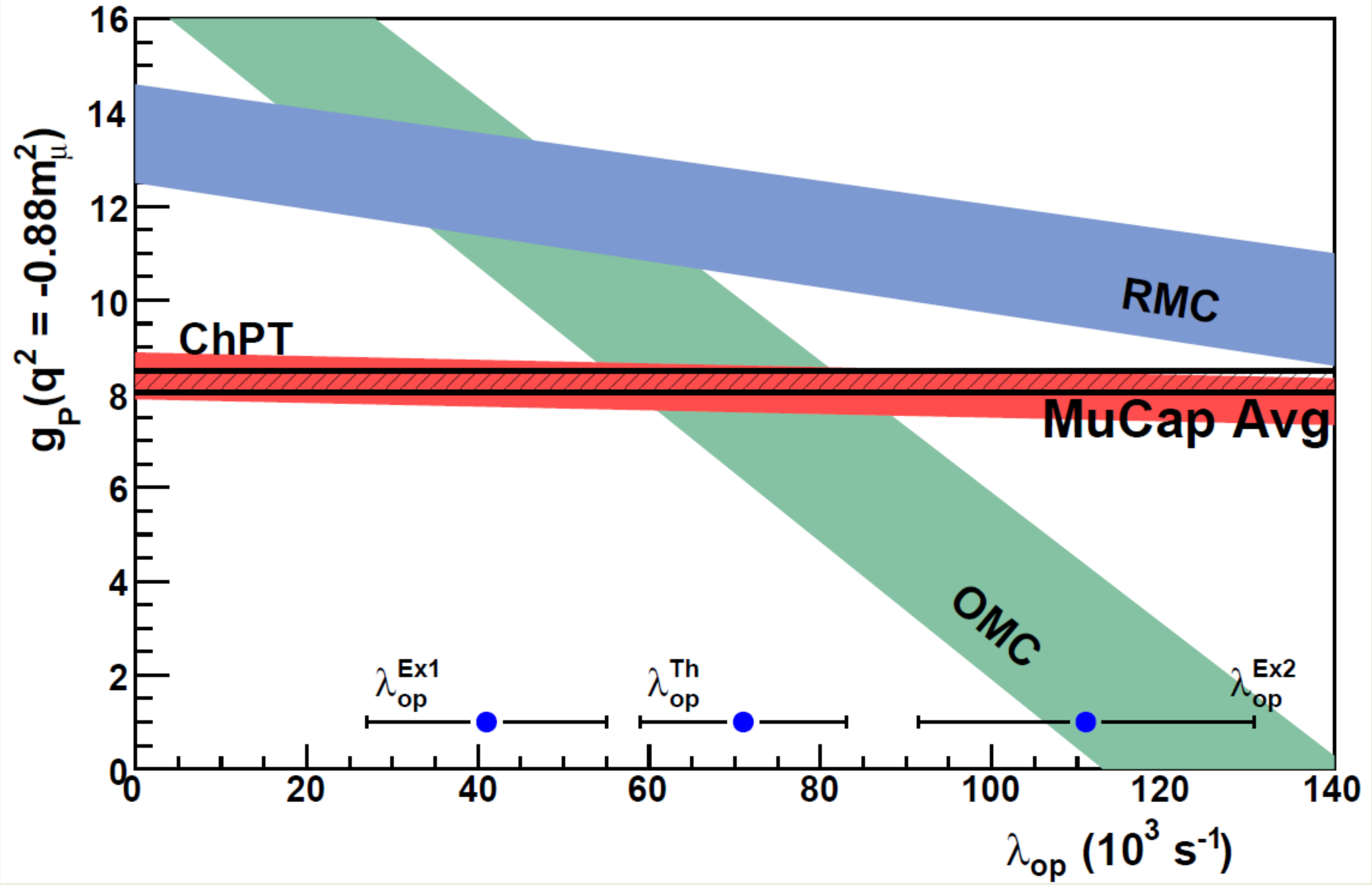
Precise and unambiguous MuCap result solves longstanding puzzle



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